

Occupant-Centric Daylight in Housing:
Daylight Availability and Occupant Visual Comfort
in Seattle Multi-Family Housing

Guanzhou Ji

A thesis

submitted in partial fulfillment of the
requirements for the degree of

Master of Architecture

University of Washington

2019

Reading Committee:

Mehlika Inanici, Chair

Rick Mohler

Program Authorized to Offer Degree:

Architecture

© Copyright 2019

Guangzhou Ji

University of Washington

Abstract

Occupant-Centric Daylight in Housing
-Daylight Availability and Occupant Visual Comfort in Seattle Multi-Family Housing

Guanzhou Ji

Chair of the Supervisory Committee:
Associate Professor, Mehlika Inanici
Department of Architecture

Housing is one of the biggest challenges in Seattle. The design decisions for floor layout and configuration of living units impact the quantitative and qualitative character of daylighting and therefore, determine daylight availability and occupant visual comfort. The goal to increase daylight availability may conflict with the need to maintain occupant visual comfort, but it is necessary to reach a suitable tradeoff. This study utilizes a simulation-based workflow for incorporating occupant-centric daylight evaluations in multi-family residential housing design starting from the schematic phases. Based on Seattle weather data, building typology of multi-family housing is studied using daylight availability and visual comfort metrics. By employing daylight analysis throughout the preliminary design, a series of design options for multi-family are developed. Comparative daylight analysis and spatial efficiency calculations are used to discuss the advantages and disadvantages of different design proposals. The results are quantification and

visualization of daylight strategies that could be taken as design guidelines by architects and developers to create well-lit spaces.

TABLE OF CONTENTS

List of Figures	iv
List of Tables	vii
Chapter 1. INTRODUCTION.....	1
Chapter 2. Seattle Housing	2
2.1 Housing in the U.S.A.....	2
2.2 Seattle Multi-Family Housing.....	3
2.2.1 Housing Market	3
2.2.2 Building Code	7
2.3 Local Climate.....	11
2.3.1 Solar Radiation and Daylight.....	11
2.3.2 Sky Cloud Cover.....	13
2.3.3 Temperature	14
2.3.4 Design Strategy.....	15
Chapter 3. Daylight Availability.....	16
3.1 Point-in-Time Daylight Metrics.....	16
3.2 Climate-based Metrics	17
3.2.1 Daylight Autonomy (DA).....	17
3.2.2 Continuous Daylight Autonomy (cDA).....	18
3.2.3 Spatial Daylight Autonomy (sDA)	18
3.2.4 Annual Sun Exposure (ASE)	19

3.2.5	Useful Daylight Illuminance (UDI)	19
3.2.6	Summary	20
Chapter 4.	Occupant Visual Comfort.....	21
4.1	Visual Discomfort.....	21
4.2	Glare Metrics	22
4.2.1	Daylight Glare Probability (DGP)	22
4.2.2	Annual Glare Probability (AGP)	23
Chapter 5.	Occupant-Centric Daylight Design	23
5.1	Daylight/Glare Metric in Residential Building.....	23
5.1.1	Current Metrics	23
5.1.2	Design Guidelines	24
5.1.3	Design Flow	25
5.2	Research Frame.....	26
5.1	Design Flow	29
5.1.1	Floor Height	29
5.1.2	Floor Typology	33
5.1.3	Window-Wall Ratio (WWR)	38
5.1.4	Shading Device	43
5.1.5	Visual Comfort.....	45
5.1.6	Floor Layout.....	52
Chapter 6.	Conclusions	56
6.1	Discussion.....	56

6.2	Design Guidelines	59
6.3	Occupant-Centric Design Flow in Residential Buildings	60
6.4	Further Study	61
	Bibliography	63
	Appendix A	67

LIST OF FIGURES

Figure 1. 2018 Top 20 Cities with Largest Apartments and Smallest Apartments in the U.S [2]

Figure 2. The number of Residential Units in construction during 2006 – 2016 [4]

Figure 3. 1995-2004's & 2005-2016's Building Construction [4]

Figure 4. 2014-2016's Mixed Use in Total Residential Construction [4]

Figure 5. Average Asking Rent/Unit & Vacancy Rate [6]

Figure 6. Unit Size and Monthly Rent [6].

Figure 7. Seattle Multifamily Top Sale Transitions in 2018 [6]

Figure 8. Seattle Zoning Maps [7][8]

Figure 9. Minimum Configuration of Stair Case (unit: inch) [9][10]

Figure 10. Site Selection [7][8]

Figure 11. Building Lot

Figure 12. Seattle Radiation (Climate-consultant 6.0)

Figure 13. Seattle Sun Shading Chart Jun-Dec (Climate-consultant 6.0)

Figure 14. Seattle Sun Shading Chart Dec-Jun (Climate-consultant 6.0)

Figure 15. Seattle Sky Cover Range (Climate-consultant 6.0)

Figure 16. Seattle Dry Bulb & Relative Humidity (Climate-consultant 6.0)

Figure 17. Seattle Psychrometric Chart (Climate-consultant 6.0)

Figure 18. Research Frame

Figure 19. Site Axon

Figure 20. Building Height Limitation

Figure 21. Wall Partition for Height Simulation

Figure 22. Height Options and UDI Simulation

Figure 23. Floor-to-Floor Height and UDI (300-3000lux)

Figure 24. Floor-to-Floor Height and Number of Floor Story

Figure 25. Floor-to-Floor Height and Total Height

Figure 26. Floor Layout Options

Figure 27. Floor Layout and UDI (300-3000lux)

Figure 28. Daylight Simulation and Spatial Efficiency

Figure 29. Wall Partitions in the Living Units

Figure 30. UDI (300-3000lux) and Wall Partitions in the Living Units

Figure 31. Window-Wall Ratio and Fenestration

Figure 32. Window-Wall Ratio 60%-90% and Energy Consumption

Figure 33. Floor Zones in Simulation

Figure 34. Window-Wall Ratio and UDI (300-3000lux)

Figure 35. Window-Wall Ratio and UDI (0-300lux)

Figure 36. Window-Wall Ratio and UDI (>3000lux)

Figure 37. Underlit Analysis for Floor Zones

Figure 38. No Shading, Point-in-Time Illuminance

Figure 39. Shading #1, Point-in-Time Illuminance

Figure 40. Shading #2, Point-in-Time Illuminance

Figure 41. Shading #3

Figure 42. View Setting for DGP

Figure 43. No Shading, DGP Simulation

Figure 44. Shading #1, DGP Simulation

Figure 45. Shading #2, DGP Simulation

Figure 46. UDI 300-3000lux for Shading Strategies in Floor Zones

Figure 47. No Shading, Annual DGP for Different Units in a Floor

Figure 48. Shading #1, Annual DGP for Different Units in a Floor

Figure 49. Shading #2, Annual DGP for Different Units in a Floor

Figure 50. Shading #3 with Automated Roller Shades (off: 300lux, on: 4000lux), Annual DGP for Different Units in a Floor

Figure 51. Final Floor Plan

Figure 52. Building Façade and Main Sections

Figure 53. Sectional Axon

Figure 54. Street View

Figure 55. Interior Perspectives

LIST OF TABLES

Table 1. DGPs Limits Level

Table 2. 3D model Objects and Radiance Material Property

Table 3. Simulation Parameter

Table 4. Point-in-Time Illuminance Comparison

ACKNOWLEDGEMENTS

For my master thesis, I got a significant amount of academic support from my thesis committee members - Mehlika Inanici and Rick Mohler. Many thanks for their time commitment to my thesis process. Thanks to Lesley Bain for sharing site information and previous design process. Thanks to Rob Kiker for desk critics during the thesis. Thanks to the final review committee members: Matthew Bissen, Rob Kiker, Joe Mayo, Enol Vallina, and Rob Peña. Thanks to the UW Department of Architecture for providing me with the tuition waiver and scholarship that support my academic journey here.

Chapter 1. INTRODUCTION

It is estimated that housing will have the largest proportion of the whole new constructions in the U.S.A in 2019 [1]. Driven by the economic growth and urbanization, Seattle has the smallest apartment size in the country [2], while the number of residential units in construction keeps increasing [3-6]. Due to the housing shortage, the number of mixed-use buildings (neighborhood commercial) in construction has exceeded the number of traditional multi-family housing during the recent decade [3-4]. The existing design codes and local policies are the constraints for housing development [7-13]. For the spatial efficiency of multi-family, the design objective is to arrange a substantial amount of living units in a single building lot [6, 14-15]. However, the limited unit size negatively impacts living comfort.

Daylight, as one of the most crucial environmental factors, is widely considered and utilized in contemporary buildings [16]. For achieving desirable daylight, various daylight metrics [17-19] were developed by researchers, and nowadays those metrics are widely used in building daylight analysis [20-29]. But most of the current daylight metrics are appropriate for commercial spaces like office buildings [30]. In residential buildings, the flexibility of floor layout and individual differences (in visual perception) [31] make it challenging to conduct daylight analysis in the design. Although the simulation-based analysis [32-33] with daylight/glare metrics are widely used for accessing daylight [34-37], the design workflow for creating occupant-centric residential spaces [38-40] is still being explored.

During the design process, spatial efficiency [14-15, 41-42], building codes [9-12], and energy consumption criteria may conflict with each other [32]. Reaching a reasonable tradeoff among those constraints is a practical challenge. A successful daylight design does not merely aim

to achieve the target illuminance, but to provide daylight strategies that can support occupant comfort and well-being.

This objective of this study is to use daylight availability and occupant visual comfort to guide the occupant-centric daylight design process in a multi-family (studio) housing in Seattle. Data analysis and graphics visualizations are used to present and compare design alternatives. Along with various constraints, the impacts of building height, floor layout (wall partitions), window-wall ratio and shading strategies are investigated at different stages.

Chapter 2. SEATTLE HOUSING

2.1 HOUSING IN THE U.S.A

In the entire construction industry in U.S.A [1], 577,085 residential buildings (single-family, Multi-family, and Improvements) are being built in 2019, and the total amount of other types of buildings amount to 765,600 (nonresidential buildings: 529,514 and nonbuilding structures: 236,086). It means that 42.98% of the new constructions in 2019 are residential buildings. Meanwhile, in those residential constructions, only 12.16% (70,156) are multi-family, and multi-family vacancy rates dropped at the historically lowest point.

The apartments sizes vary in different American cities. A report [2] shows that the average rent of new-built apartments has increased 28% compared to the data 10 years ago, but the size of an apartment has gotten 5% smaller by the end of 2018. In the ranking of the top 20 smallest apartments (Figure 1), Seattle is in the first place with an average apartment size of 711 sq.ft. In contrast to the largest apartments ranking, the average apartments size in Tallahassee (1,038 sq.ft) is almost 300 sq.ft larger than the one in Seattle. Accommodating occupants in such limited living spaces is a challenge for architects.



Figure 1. 2018 Top 20 Cities with Largest Apartments and Smallest Apartments in the U.S [2]

2.2 SEATTLE MULTI-FAMILY HOUSING

2.2.1 Housing Market

Seattle has seen major economic development, population growth, along with increased housing demand in recent decades. According to the 2005's Comprehensive Plan by the Department of Planning & Development - the city of Seattle [3], 47,000 new households are being planned as a response for the housing demand during the period of 2004 - 2024, with the addition of 84,000 new job positions. The Building Construction Permits (Figure 2) shows the number of new-built residential units increased consistently from 2006 to 2016. In some years (i.e., 2009, 2010), the increase is not as high as others. It is possible that the developers responded to the housing market

in different ways, when the overall housing market is in a boom or cool-down state. The number of demolished units fluctuated accordingly with the overall growth of new-built units. Overall, Seattle housing is in a growing phase.

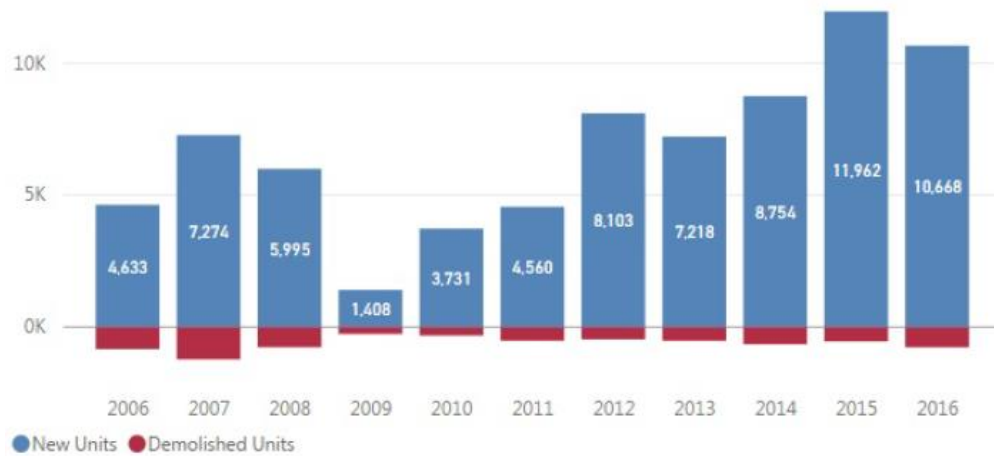


Figure 2. The number of Residential Units in construction during 2006 – 2016 [4]

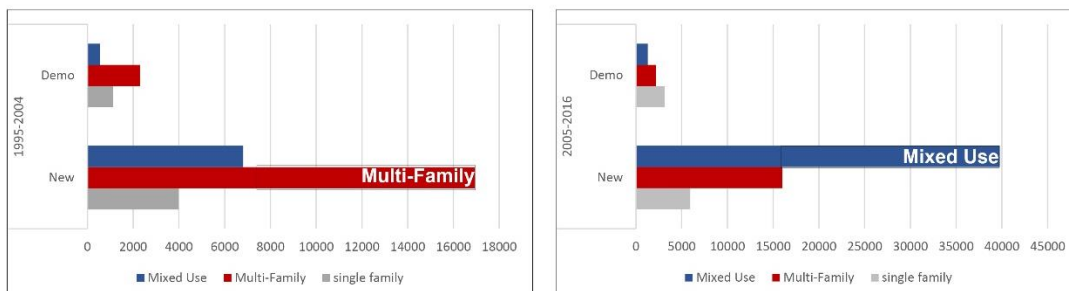


Figure 3. 1995-2004's & 2005-2016's Building Construction [4]

Between 1995 and 2004, most of the new-built residential units are multi-family, while the mixed-use buildings comprise less than half of the whole new construction (Figure 3). From 2005 to 2016, the majority of new construction is mixed-use building. The number of multi-family, which leads the new construction during period of 1995-2004, dropped dramatically (Figure 4).

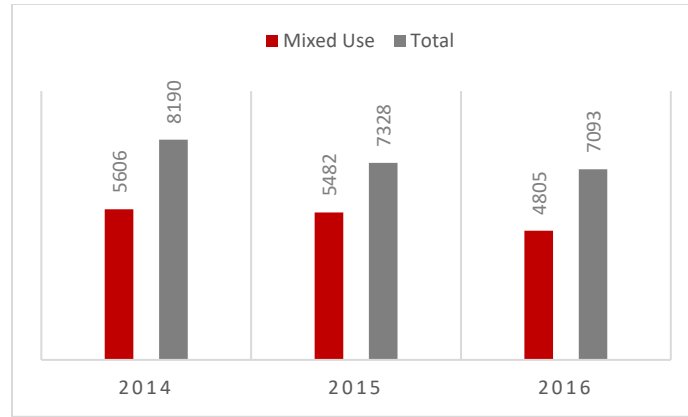


Figure 4. 2014-2016’s Mixed Use in Total Residential Construction [4]

Figure 4 shows that during 2014 and 2016, more than 7,000 new residential buildings are constructed yearly and most of them are mixed-use buildings. Thus, multi-family, especially in mixed-use building type, accounts for most of the residential constructions recently.

Neighborhood commercial is a common mixed-use building type. It has two functionalities - ground commercial area and multi-family units in the upper floors. The prevalence of mixed-use buildings could be interpreted that due to the limited land-use and increasing housing demand, this typology encourages more living units combined commercial space in a single building lot.

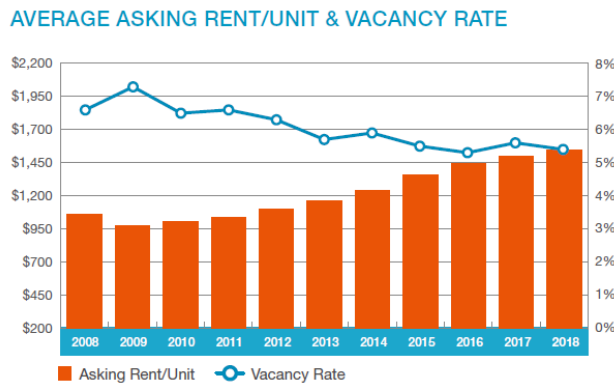


Figure 5. Average Asking Rent/Unit & Vacancy Rate [6]

In the economy aspect, Washington State ranks the third (after Hawaii and California) in the ranking of the expensive state in building a house in U.S.A [5]. The latest Seattle Multi-Family

Report (by 2018 fourth quarter) [6] reveals that the price of asking Rent/Unit has been raised approximately from \$950 to \$1,500 since 2009, but the vacancy rate has dropped to approximately to 5.3%.

Average Rent	
Unit Size	Monthly Rent
Studio	\$1,314
1 Bedroom	\$1,448
2 Bedroom	\$1,659
3 Bedroom	\$1,891

Figure 6. Unit Size and Monthly Rent [6]

As seen in Figure 6, monthly rent for a studio is \$1,314, and 1-Bedroom costs \$1,448/month. For units with more than one bedroom, the monthly rent goes up, when the number of bedrooms increases. 3-Bedroom is the cheapest living space regarding the rent cost, since multiple people can share the lease. But living in multi-bedroom units poses privacy issues. Comparing the price in the intersection of asking rent and vacancy rate, studio and 1 bedroom are the most feasible options.

Property	Submarket	# of Units	Sale Price	Price/Unit
Avana 522	North Creek	558	\$173,000,000	\$310,036
Sparc	Bel-Red	309	\$150,000,000	\$485,437
The Reserve Apartments	South Lake Washington	440	\$143,000,000	\$325,000
The Griffis Residential	South Lake Washington	440	\$139,500,000	\$317,045
Cirrus	Denny Triangle	355	\$103,296,401	\$290,976

Figure 7. Seattle Multifamily Top Sale Transitions in 2018 [6]

Avana 522 ranks the top in 2018's multi-family sale transactions (Figure 7) with the largest number of units (558). Although the most expensive unit is in Sparc, due to its lower number of

units, the total sale price ranks the second (the housing projects here might cover condo housing and other housing types). The transaction statistics generally shows that the price/unit and the number of units are two main factors that determine the total sales price in housing market.

The studio/1-Bedroom is the top choice for the living comfort. However, single unit space costs much more than those living units with multiple bedrooms, and it serves fewer people than those in 2 or 3-Bedroom units. From the standpoint of economy, a large number of units raise the over sale price remarkably. Although multi-bedroom units are more economical for dwellers, they are not feasible as studio/ 1-Bedroom involving living comfort and housing market.

2.2.2 *Building Code*

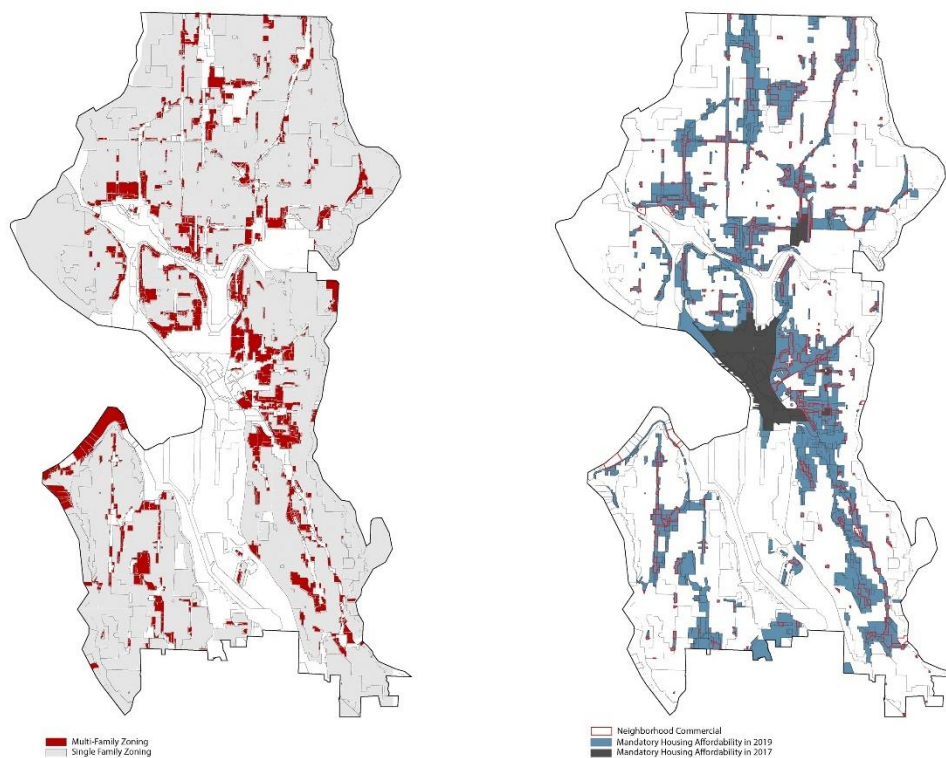


Figure 8. Seattle Zoning Maps [7] [8]

According to the Seattle zoning, the multi-family zoning areas are in the surrounding of the downtown, and the overall distribution is fragmentary. As a Seattle-based housing policy, Mandatory Housing Affordability (MHA) [8] ensures a particular amount of affordable housing in the new-built commercial/multi-family projects. In this case, a specific building will receive height incentives in the future. In 2017, the planning area of MHA primarily concentrated in the downtown district; in 2019, it will be applied in more individual regions. By overlapping the planning area of MHA and neighborhood commercial, the target area of MHA in 2019 covers the zoning area of the neighborhood commercial.

This study refers Seattle Building Code [9], Seattle Fire Code [10], and Common Seattle Residential Code Requirements [11] and determines the minimum interior dimensions:

- (a) Ceiling Height: 7'-6";
- (b) Ground Level Height: 14'-0" (13'-0" in code [12], 1'-0" for structural space)
- (c) Corridor (exit passageway): 44";
- (d) Door opening: 34" (32" in building codes[9,10], 2" reserved for hinge connection);
- (e) Room width: 7'-0" in any dimensions;
- (f) Wall partitions: living units partitions: 9";
- (g) Corridor/interior wall: 6";
- (h) Stair case: as Figure 9. shows, it satisfies the minimum requirement in fire code.
- (i) Elevator: Manufacturer-Otis [13], elevator for mid-rise building, reserved floor space for elevator is 88" by 88" (2,235mm by 2,235mm), with machine room in the roof.

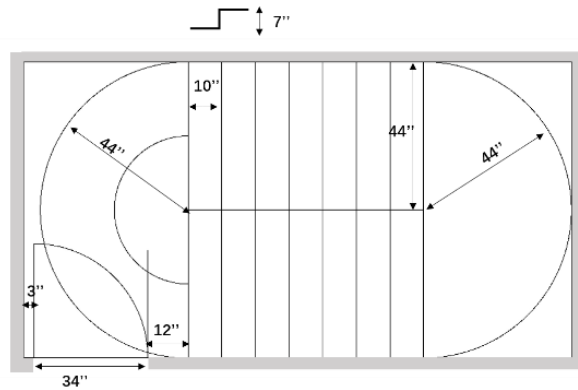


Figure 9. Minimum Configuration of Stair Case (unit: inch) [9][10]

The minimum unit size for Small Efficiency Dwelling Unit (SEDU) is 220 sq.ft and the minimum size of a typical studio is 300 sq.ft. Due to some practical restrictions, the size of SEDU will reach 250 to 270 sq.ft [14, 15]. In order to explore the balance between unit size and number of units, this study sets the target unit size within the range of 220 sq.ft and 300 sq.ft and only focuses on single floor.

The selected site is located in the Capitol Hill, at the northeast corner of East Pike Street and 12th Avenue (Figure 11). It satisfies three criteria: (a) The location is in the Seattle zoning area for multi-family and neighborhood commercial; (b) To respond to the local policy (MHA), the site is in the 2019's MHA zoning area; and (c) The building lot has a regular geometry and orientation.

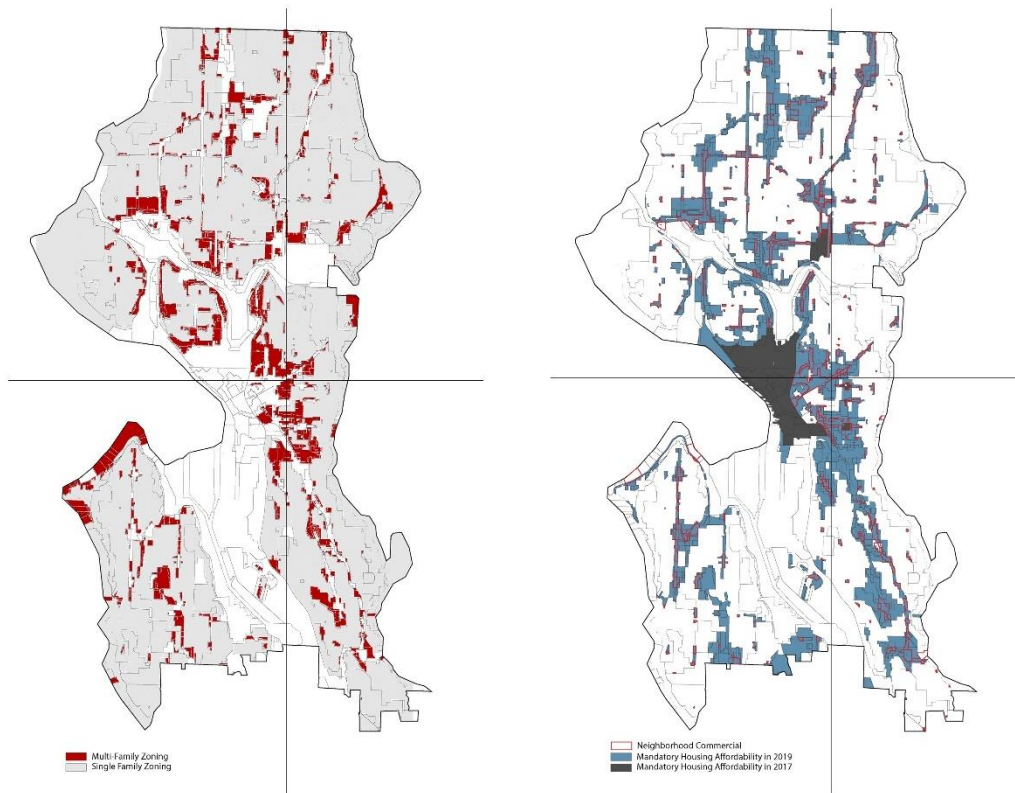


Figure 10. Site Selection [7][8]

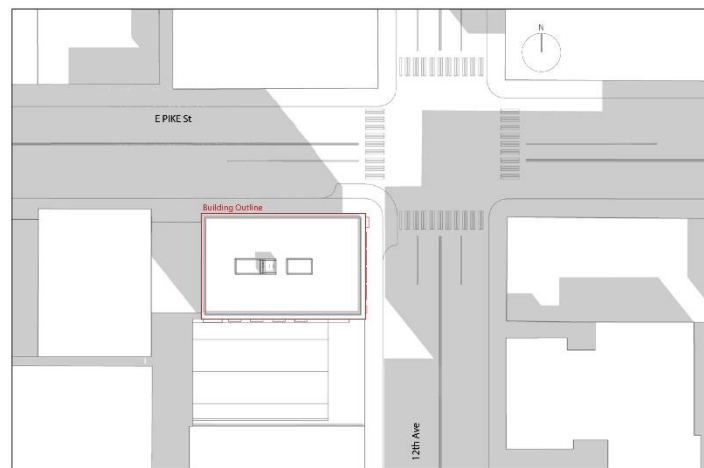


Figure 11. Building Lot

The building lot (90'-0" by 57'-6") is exact a North-South orientated rectangle, with the extension in the West-East. The existing building is a multi-family project - Agnes Loft. It

combines neighborhood commercial at the street level and twenty-four double height's living units at the upper level. As the height limitation increases from 65' to 75' [8], more floor stories would become available for construction in the future.

2.3 LOCAL CLIMATE

2.3.1 *Solar Radiation and Daylight*

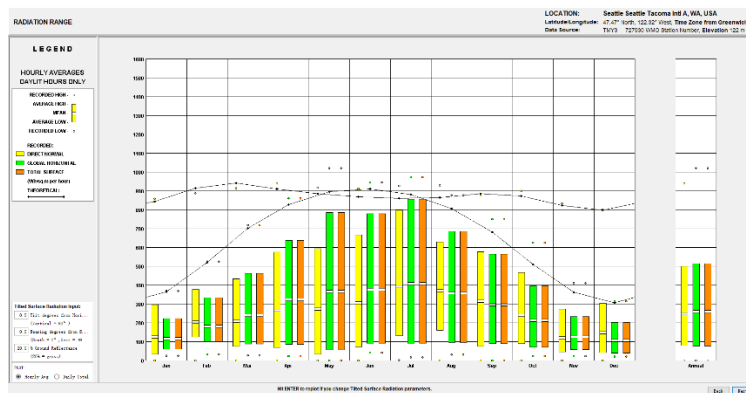


Figure 12. Seattle Radiation (Climate-consultant 6.0)

Direct normal radiation is a measurement of solar rays at a perpendicular angle, and global horizontal radiation is the measurement of radiation on a horizontal surface from both the sun and sky. The global horizontal solar radiation in summer (850W/sq.m per hour) is much higher than the winter (e.g. December and January values are approximately 200-300 W/sq.m per hour). The solar radiation in transition seasons is within those two threshold values. Direct normal radiation can reach 0 W/sq.m per hour on some overcast winter days. Daylight is the visible portion of the solar radiation, and it is measured in Lux (or foot-candle).

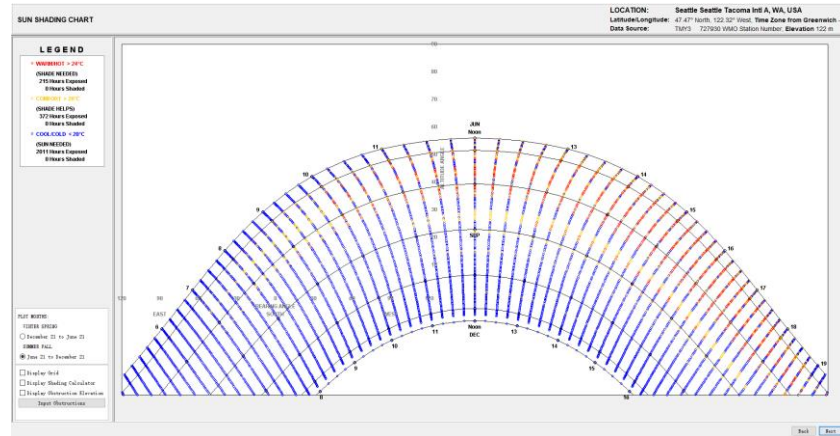


Figure 13. Seattle Sun Shading Chart Jun-Dec (Climate-consultant 6.0)

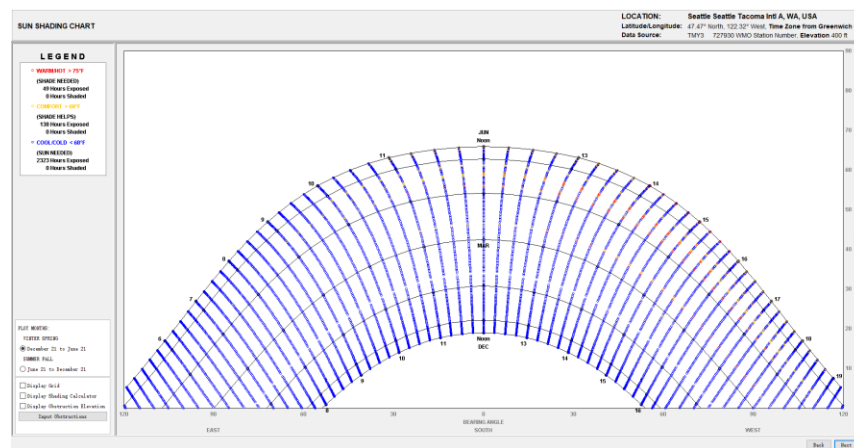


Figure 14. Seattle Sun Shading Chart Dec-Jun (Climate-consultant 6.0)

Figure 13 shows the sun altitude and bearing angle between June 21st and December 21st in Seattle. Within those 6 months: (a) 215 hours are warm/hot ($>24^{\circ}\text{C}$), shading is needed; (b) 372 hours are within the comfort range ($>20^{\circ}\text{C}$); and (c) 2011 hours are cool/cold ($<20^{\circ}\text{C}$), solar radiation is desirable. Figure 14 shows the sun altitude and bearing angle between December 21st and June 21st in Seattle. Within those six months, (a) 49 hours are warm/hot ($>24^{\circ}\text{C}$), shading is needed, (b) 138 hours are within comfort range ($>20^{\circ}\text{C}$); and (c) 2323 hours are cool/cold ($<20^{\circ}\text{C}$).

Overall, in Seattle 84.85% time (when temperature $< 20^{\circ}\text{C}$ /whole years hours) needs sunlight. 9.98 % time (comfort range $>20^{\circ}\text{C}$) could get help from sun shading, and only 5.17%

time (warm/hot range $>24^{\circ}\text{C}$) needs shading. However, it should be noted that these are outdoor conditions. Indoor occupant visual comfort, thermal comfort, and energy use may differ significantly depending on the design; and occupant visual comfort prompts more shading control than thermal comfort and energy considerations. The design criterion in this thesis is defined as to add direct shading strategy when it is needed. The target time range is from 10:00 AM to 6:00 PM between June and September and from 11:00 AM to 6:00 PM between March to June.

2.3.2 Sky Cloud Cover

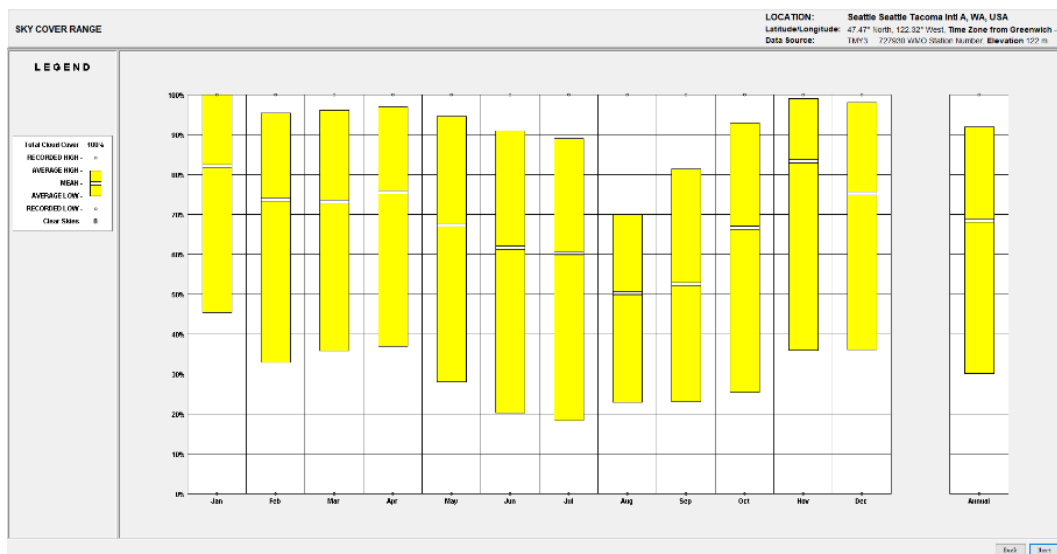


Figure 15. Seattle Sky Cover Range (Climate-consultant 6.0)

Sky cover in Seattle is at a high level with a changeable range monthly:

(1) Average Mean: In January and November, the average percentage of sky cover is above 80%. During February, March, April, and December, the percentage of sky cover is within 70%-80%. For the rest of the year, the mean percentage of sky cover is still above 50%.

(2) Average High/Low: Average highest sky cover exceeds 90% in 9 months. During January, November and December, the percentage of sky cover almost reaches 100%. The lowest level is

around 20% during June and July. For the rest of the year, it is between 20% and 50%. The percentage of sky cover has a monthly significant fluctuation.

(3) Recorded High/Low: Each month has a record between 0% and 100% sky cover. Similar to the data of average High/Low sky cover throughout the whole year, sky cover varies between 0 to 100% within one month or even one day.

2.3.3 Temperature

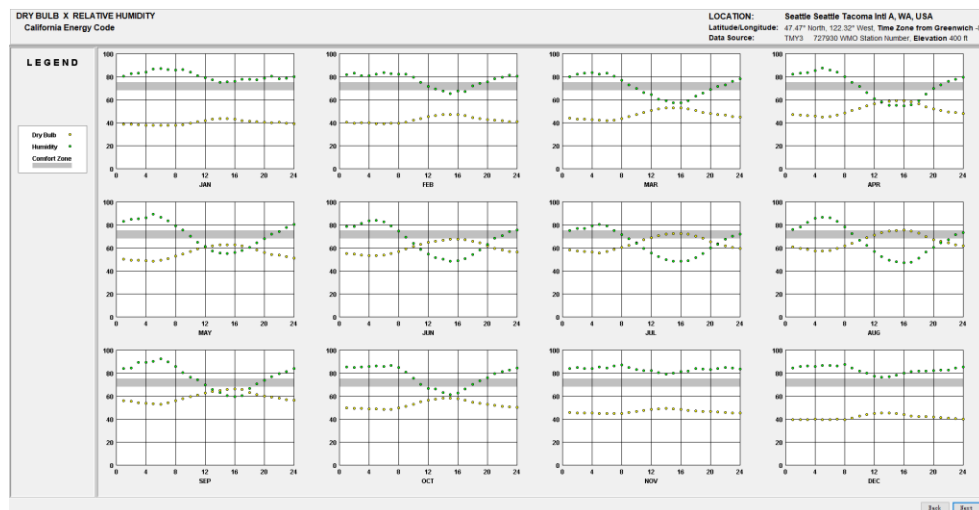


Figure 16. Seattle Dry Bulb & Relative Humidity (Climate-consultant 6.0)

The average comfort temperature is between 70° and 75°F. The dry bulb temperature is below the comfort zone during most of the time. In July and August, the dry bulb temperature value reaches the comfort zone between noon to evening. The humidity is within the range of 40%-90% throughout the whole year. During November, December and January, the value of humanity is stable at the level of 80% or so. Whereas in the other months, the humidity typically reaches the highest point at 4:00 AM and drops at the lowest continuously until 4:00 PM. Then it rises again and repeats this daily fluctuation.

2.3.4 Design Strategy

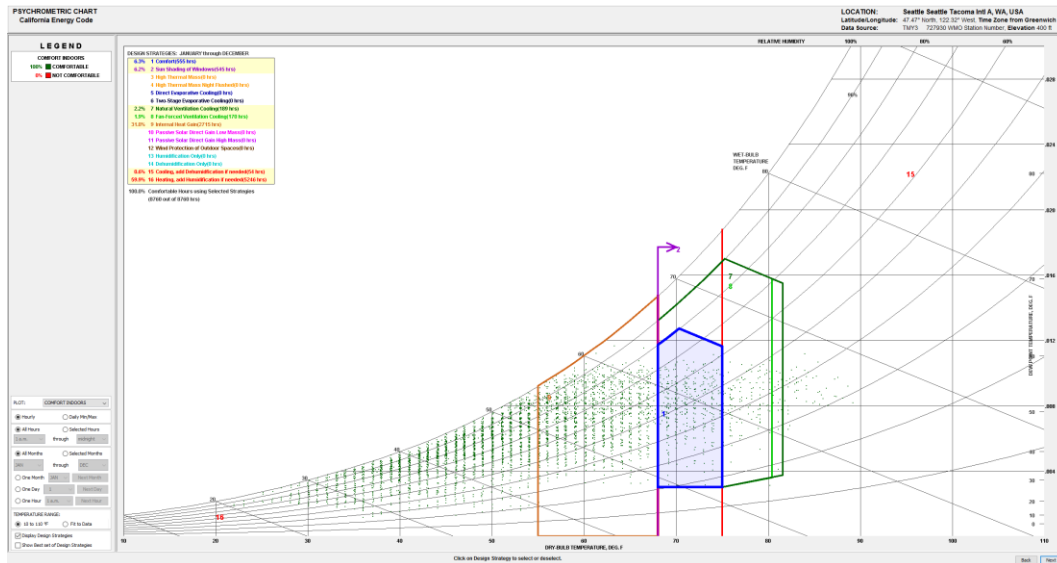


Figure 17. Seattle Psychrometric Chart (Climate-consultant 6.0)

The psychrometric chart (Figure 17) shows: (1) Internal heat gain (mainly from occupants and mechanical systems) could improve living comfort. But the number of occupants and mechanical load are low in the individual living units (multi-family housing). Thus, it is not an effective strategy for this study. (2) Mechanical means (heating and humidification) increase comfort by 58.9%. Considering the over sky cover is high in Seattle, it results in low passive solar gain for buildings, and heating is necessary. (3) Heating has more significant effects in improving living comfort than cooling. To minimize the heat loss, the facade with low window-wall ratio (WWR) is idea but may conflict for achieving desirable daylight levels. When high WWR is used, it is recommended to use multi-glazing (or energy efficient glazing) to balance between the heating loss and daylight availability. (4) Natural ventilation facilitates living comfort, and the operable window will be favorable.

Overall, Seattle weather is relatively mild. The psychrometric chart provides architectural guidelines to facilitate living comfort. In terms of daylight, the solar radiation in the summer is

higher than winter and transitional seasons. Shading will be needed between March and September, especially during the summer months (due to the low sky cover). Shading strategies in this study will be based on physical daylight penetration and visual comfort, without counting for thermal comfort.

Chapter 3. DAYLIGHT AVAILABILITY

Daylight is the interplay of natural light and building form that provides a visual stimulating, healthful and productive interior environment. Due to technological developments (i.e., lighting fixtures, glazing materials, and daylight apertures), design strategies for utilizing daylight have continuously been varied since the 20th century [16,17]. Meanwhile, designers' ability in computing the dynamic nature of daylight has advanced as well. The daylight simulation tools, like climate-based daylight modelling (CBDM) [18], are widely adopted in the architectural industry [19]. A previous survey shows that around 89% of people (researchers, engineers and designers) incorporated daylight in their design projects [20]. Despite the advancement in computational tools that facilitate daylight design, there are still not definitive agreements on: (1) what makes it a good daylight design; (2) what are the main goals to achieve in daylight design; and (3) what kind of design guides and daylight standards are needed, especially within the context of residential buildings.

3.1 POINT-IN-TIME DAYLIGHT METRICS

For point-in-time metrics, a typical date and specific time point will be selected (i.e., June 21st, 3:00 PM). When the comprehensive daylight analysis is needed, multiple dates (i.e., solstices and equinoxes) and time points (i.e., 9:00 AM, 12:00 PM, 3:00 PM) are needed for addressing the daylight variability. The same date and time points might have different sky conditions in different

years (i.e., CIE clear, overcast, and intermediate skies). The analysis of point-in-time illuminance is to study the typical daylight situations at the key dates/times, under probable sky conditions.

Choosing multiple dates with different sky conditions for daylight simulation is a typical simulation practice, but the substantial time cost is the practical limitation for using the point-in-time metric. In simulation, using typical dates (two solstices and two equinoxes) and time points (i.e., 9:00 AM, 12:00 PM, 3:00 PM) with three main sky conditions will create a large number of simulation scenarios and data results. Additionally, the result from a single point-in-time simulation may not be representative of the annual daylight performance.

3.2 CLIMATE-BASED METRICS

A daylight metric with annual meteorological data, thus, becomes a necessity for responding to the physical environment. With the local weather data, the annual-based simulation provides more realistic results in long-term daylight performance. Unlike the hourly illuminance, a specific period (i.e., 8:00 AM-6:00 PM) during the whole year will be selected as occupancy schedule, depending on the functionality of the building.

Daylight Factors (DF) was widely used as a point-in-time and annual-based metric in the past. But DF is not applicable for daylight analysis when sky condition, location and building orientation are considered [16-18]. In few current rating systems [21-24], DF is still being used [23], but its use is limited [25].

3.2.1 *Daylight Autonomy (DA)*

Daylight Autonomy (DA) uses the percentage of the whole year during daylight hours to quantify whether a target space (or a measurement point) received sufficient daylight, given a minimum illuminance threshold. The illuminance threshold could be based on the functionality of the space.

The availability of direct sunlight strongly impacts the daylight illuminance, and DA doesn't enforce an upper threshold [17, 26].

3.2.2 *Continuous Daylight Autonomy (cDA)*

Continuous Daylight Autonomy (cDA) is proposed by Rogers in 2006, based on the daylight research in a classroom space. In comparison to other daylight metrics (with strict threshold), the transition between compliance and noncompliance is softened in cDA [17]. Partial credits are given to the areas that have slightly lower illuminance than threshold. It doesn't exclude the daylight which contributes to the overall illuminance. For instance, when the target illuminance is 300lux, those areas with 280 lux or 290 lux illuminance could acquire the cDA credits as their proximity to the target value. Similar to DA, there is no upper threshold in cDA, so it doesn't penalize for glare.

3.2.3 *Spatial Daylight Autonomy (sDA)*

Spatial Daylight Autonomy (sDA) is a measure of daylight illuminance sufficiency for a given area, which reports a percentage of floor area (>50%) that exceeds a specified illuminance (e.g. 300lux) for a specified percentage of the analysis period (Illuminating Engineering Society (IES LM-83-12)). Wymelenberg and Mahić [27] describe sDA as a metric that "examines whether one space receives enough daylight during standard operating hours (8:00 AM to 6:00 PM) on an annual basis using hourly illuminance grids on the horizontal work plane". The value of sDA result ranges from 0 to 100%. If the result value is above 75%, the daylight in the space is regarded "preferred". If it is in the range of 55%-74% of the year, the daylight in this area is "accepted".

3.2.4 *Annual Sun Exposure (ASE)*

Annual Sun Exposure (ASE) is the fraction or percentage of the horizontal work plane that exceeds a specified direct sunlight illuminance level more than a specified number of hours per year over a specified daily schedule with all operable shading devices retracted (Illuminating Engineering Society (IES LM-83-12)). ASE measures horizontal illuminance based on an annual basis, and it means it is not a glare metric [27]. However, it is developed for preventing excessive daylight levels that potentially lead to glare issue. ASE serves as a complementing metric for sDA. The sDA above 75% indicates it is sufficient daylight. It cannot not predict excessive daylight that may cause glare and overheat issue.

The ASE restricts direct sunlight penetration into space (<250 hours permitted annually), which makes it strict for daylight design [18]. In most cases, the overlit areas are near the windows. A strict ASE value might be necessary for commercial buildings, but more leniency should be exercised in residential buildings.

3.2.5 *Useful Daylight Illuminance (UDI)*

In order to compare daylight availability with a single metric (with different thresholds), Useful Daylight Illuminance (UDI) was proposed by Mardaljevic and Nabil in 2005 [17, 28]. The result of UDI provides a low and a high illuminance target separately for the given space. Three UDI ranges were specified initially (UDI 100-2000lux), exceeded (UDI >2000lux), and feel-short (0-100 lux) [18, 25]. After further research [29], the current UDI ranges are:

- (1) UDI “underlit”, illuminance is less than 100lux;
- (2) UDI “supplementary”, illuminance is between 100lux and 300lux;
- (3) UDI “autonomous”, illuminance is between 300lux and 3000lux;

(4) UDI “exceeded”, illuminance is higher than 3000lux.

As DA has no upper threshold, when DA sets 300lux as its threshold, $DA_{300} = UDI(300-3000lux) + UDI(>3000lux)$ [29]. For UDI simulation results (like UDI 300-3000lux), a building space, which has the concentration of low illuminance, might achieve the same UDI value with another space, which has the relative more extensive illuminance range and a higher maximum illuminance. The illuminance distribution at a single point-in-time across the year cannot be demonstrated from the numerical value of UDI simulation. If designers need insight into daylight performance, both point-in-time false-color maps and UDI values are needed.

3.2.6 *Summary*

Daylight metrics are primarily based on a horizontal simulation plane. 300lux is a well-accepted threshold for visual tasks [21-24]. Among annual-based metrics, UDI (300-3000lux) could guide desirable daylight design, and UDI (>3000lux) predicts the area with potential glare issues. Most of current daylight metrics are applicable for commercial buildings, and there is not a specialized daylight metric targeted for residential buildings at the time being [30].

For residential buildings:

(1) Occupancy Profiles: the occupancy schedules are relatively easy to determine in an office building or classroom (9:00 AM-5:00 PM for offices and 9:00 AM-3:00 PM for k-12 schools). During daytime, 8:00 AM-6:00 PM is assumed as the occupancy schedule in residential buildings, despite the occupancy presence and daily activities are unpredictable.

(2) Glare Prediction: The glare area (overlit area) could be predicted from ASE and UDI (>3000lux). When ASA or UDI (>3000lux) demonstrates the overlit area, it is usually near windows. While glare could be alleviated by limiting the sun penetration, the daylight availability in the deep interiors drops as a direct consequence. In living units, a change in body position or

furniture layout would suffice to address the offending interaction between occupants' eyes and uncomfortable daylight. Therefore, the glare prevention in residential building is not as strict as commercial spaces.

Chapter 4. OCCUPANT VISUAL COMFORT

4.1 VISUAL DISCOMFORT

Human's visual system processes luminance variation in a wide range (from 0 to 10,000,000cd/m²). When an object with high luminance appears in the visual field, the typical human behavior is to blink eyes or look away from the light source [30]. Insufficient visual contrast, direct sunlight, and discomfort glare are three main factors that cause occupants' visual discomfort. Discomfort glare occurs when bright light sources cause visual irritation or eyestrain. As a subjective phenomenon that is related to occupants' satisfaction, discomfort glare is more subtle than disability glare [32]. In interior spaces, discomfort glare is far common than disability glare [33]. In residential buildings, window openings are the primary source of light. The glazing size, building location, and orientation all impact the occupants' perception of discomfort glare [34].

Along with the direct sunlight, the reflections of sunlight from other surfaces cause visual discomfort [29]. Due to different age, gender, and previous experience in visual tasks, occupants have different perceptions, responses, and preferences to daylight [31]. An individual's perception may vary from season to season as well. There is a higher acceptance of sunlight presence in winter (compare to summer) [35]. Instead of discussing the individual differences, this study will predict glare issues for the majority of people.

4.2 GLARE METRICS

4.2.1 Daylight Glare Probability (DGP)

There are a variety of glare metrics, like Daylight Glare Index (DGI), CIE Glare Index (CGI), CIE's Unified Rating Systems (UGR). Those metrics have both merits and shortcomings [33, 35]: (1) Except for DGI and DGP, all metrics are developed for artificial lights. In this case, they are not suitable for evaluating glare that is caused by natural sunlight; (2) Glare is closely related to the individual view, so the glare sensation changes rapidly depending on view position/angles. Metrics calculate glare on a single viewpoint; (3) There is a lack of consideration for individual differences and seasonal variations of daylight.

$$DGP = c_1 E_v + c_2 \log \left(1 + \sum_i \frac{L_{s,i}^2 \omega_{s,i}}{E_v^c P_i^2} \right) + c_3$$

Equation 1. DGP Equation

Wienold and Christofferson first developed daylight Glare Probability (DGP) in 2006. E_v -vertical eye illuminance (Lux), L_s -luminance of the source (cd/m²), ω_s - Solid angle of source, and P-position index are incorporated in an equation. A glare source is typically the visual area with the luminance at least five times higher than the average scene luminance [36]. DGP accounts both contrast and brightness, as well as scene luminance [37]. Therefore, it is currently the most reliable metric to predict glare issues. It reports the percentage of people who feel the scene glary. In 2009, Wienold [29] specified the levels of glare, and three thresholds are used to identify imperceptible, perceptible or disturbing glare. Three glare categories (Table 1) are specified as: (1) A: best, imperceptible; (2) B: good, perceptible; and (3) C: reasonable, disturbing.

Class	A	B	C
95% DGPs limit	≤ 0.35	≤ 0.40	≤ 0.45
Mean DGPs (5%)	< 0.38	< 0.42	< 0.53

Table 1. DGPs Limits level

Currently used four glare levels are: (1) Intolerable glare, $DGP \geq 45\%$; (2) Disturbing glare, $45\% > DGP \geq 40\%$; (3) Perceptible glare, $40\% > DGP \geq 35\%$; and (4) Imperceptible glare, $45\% \geq DGP$.

4.2.2 *Annual Glare Probability (AGP)*

Annual Glare Probability (AGP) is an annual-based metric based on single viewpoints which is similar to DGP. In contrast to the instantaneous metric - DGP, it provides a graphic chart (with glare levels). Although such a statistical chart could not indicate which areas are prone to glare issue specifically, it could share the same view setting with DGP and serves as a supplement for analyzing the long-term glare issue.

Chapter 5. OCCUPANT-CENTRIC DAYLIGHT DESIGN

5.1 DAYLIGHT/GLARE METRIC IN RESIDENTIAL BUILDING

5.1.1 *Current Metrics*

Most of the daylight research focuses on work environments (i.e., office space) rather than residential spaces [30][38]. Some certain building types (i.e., healthcare facilities) need higher requirements of illuminance [21]. Desirable lighting thresholds for residential buildings is still in debate [38-40]. There is more flexibility in occupant activities/schedule and furniture layout in residential units, and there are different tasks and task surfaces with different illuminance requirements. Form finding by maximizing adequate levels of daylighting is directly relevant to a

successful residential design. It is challenging to use a single metric to evaluate daylight. A more acceptable approach is to explore current daylight metrics as a collection of analysis tools [30, 39]. Using both point-in-time and annual-based metrics are needed to address the daylight issues in a residential space.

5.1.2 *Design Guidelines*

Current daylight design lacks a precise method to evaluate daylight quality and its effect on human vision [20]. In architectural practice, the rules-of-thumb is still widely utilized as common sense - the larger the window size, the better natural daylight. However, due to the high levels of daylight admission and the associated propensity for glare, full-glazed building poses many problems in daylight and visual comfort [25]. It is necessary to balance abundance of illuminance with occupant visual comfort. This approach can guide the design of window openings and building façades.

Sustainability rating systems specify criteria (partially selected here) in daylight: (1) BREEAM (UK) [21] specifies that the target period (at least 2650 hours/year) for desirable daylight illuminance (at least 300 lux); (2) In the LEED [22], spatial daylight autonomy 300/50% (sDA300/50%) is set as daylight target; (3) Human-comfort based standard - WELL [24] adopts the minimum percentage of the area (55%) that achieves 300 lux during 50% operating hours (Spatial Daylight Autonomy (sDA300, 50%)). All of those rating systems take 300 lux as the benchmark for visual tasks, with time periods and target percentage of floor area. The annual-based metrics are widely accepted in those rating systems. Yet, the overall ratio of the target area doesn't differentiate functions/orientations of the building floor. Spaces like hallways and closet are necessary, but they do not necessarily need access to constant daylight.

Since the 300 lux is commonly recognized as the minimum illuminance for human activities, it is reasonable to adopt it as a low threshold in the residential building design/simulation; 3000lux is the common upper threshold for overlit [21-24]. Taking the 300-3000lux for annual-based simulation will exclude most of the illuminance in either underlit (0-300lux) or overlit (>3000lux). This illuminance range provides both straightforward guidelines and design flexibility for architects. The simulation grid is set to an imaginary plane at table height (2.5ft). Most visual activities take place in this plane (kitchen counter, dining table, and reading a book) in residential buildings. As visual comfort strictly depends on the view position/directions [36], the target areas are supposed to be outlined more specific when conducting glare analysis.

5.1.3 *Design Flow*

Rating systems usually divides design process into building design, building construction, and post-occupant evaluation. The target illuminance value works as a benchmark for daylight design, but it also increases the workload for the design teams [32]. However, if early design decisions (i.e., floor height, floor layout and window wall ratio) have already been made without considering target illuminance, it then becomes more challenging to optimize interior daylight and occupant visual comfort at later stages of design. The necessity here is to bring daylight/glare simulation data into the earlier design stage. The primary obstacles for computational simulation are [32]: (1) the technical complexity and time cost; (2) utilizing appropriate simulation programs; and (3) interpretation of simulation results. The previous study [36] has recommended that daylight performance metrics should consider daylight availability and glare issues together. Because of the different measurements in the daylight metrics (illuminance) and glare metrics (luminance), the connection between daylight availability and visual comfort should be simultaneously considered.

Daylight doesn't merely influence occupants' visual comfort, but it impacts energy-usage and spatial perception [16]. Under various constraints, it may be impossible to achieve those design objectives all together [32]. A design decision for realizing desirable daylight could impact negatively on spatial efficiency; a design decision targeted on energy efficiency may not be suitable for occupants' living comfort [20].

Overall, annual-based metrics (UDI, Annual DGP) help designers to better understand long-term daylight performance and make informed design decisions. This study uses UDI for annual-based daylight simulation, and the height of simulation plane will be fixed in 2'-6". Only the floor areas in the main living space are included in the resultant analysis. Point-in-time metrics (illuminance and DGP) are used to predict instantaneous daylight/glare issues at typical time points.

5.2 RESEARCH FRAME

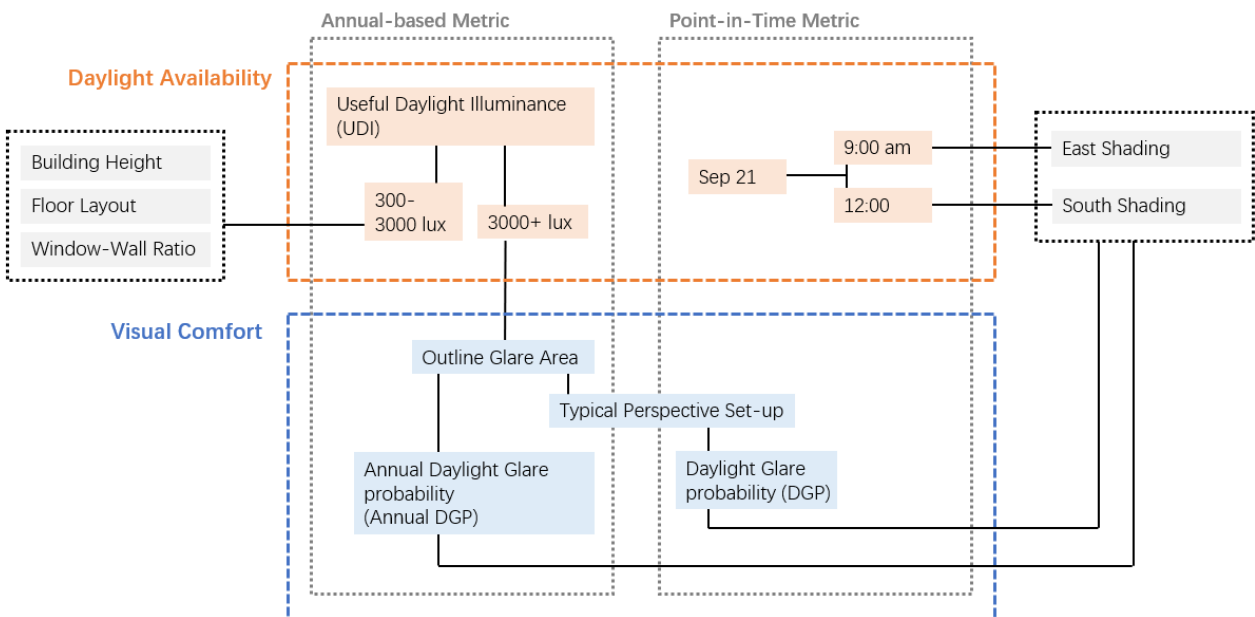


Figure 18. Research Frame

The research frame is a simulation-based design flow (Figure 18) that combines daylight analysis and glare prediction comprehensively. For the annual-based daylight, UDI (300-3000lux) is introduced as the target illuminance range to guide the design decisions, such as building height, floor layout, and window-wall ratio. The point-in-time metric is based on September 21st as the typical date (equinoxes) for shading design, so that the shading period covers from March 21st to September 21st. DGP is used to test the impact of shading on human visual comfort on September 21st, 9:00 AM and 12:00 PM. Design flow uses the (UDI >3000lux) to predict the overlit area. As the glare metrics - DGP and Annual DGP - share the same view setting, the results provide information on selecting long-term and instantaneous shading devices. The workflow facilitates the objectives of well daylit and comfortable design by specifying the sequence of analytical steps for evaluating daylight availability and visual comfort.

The simulation objects were all modeled with NURBS geometry in Rhino. Grasshopper is used as a supplement tool. Annual-based simulations (UDI, Annual DGP) are conducted by DIVA-for-Rhino with Radiance simulation engine. Point-in-Time simulations (hourly illuminance, DGP) are processed through DIVA Grasshopper interface for quick feedback/testing of the impacts of different design alternatives.

Table 2. 3D model Objects and Radiance Material Property

Object	Radiance Material Property
Surrounding Buildings	35% Diffuse Reflectance
Ceiling	80% Diffuse Reflectance
Floor	20% Diffuse Reflectance
Roof	35% Diffuse Reflectance
Ground	20% Diffuse Reflectance
Wall	70% Diffuse Reflectance
Interior Door	50% Diffuse Reflectance
Shading	35% Diffuse Reflectance
Window (Glazing_DoublePane_Clear)	80% Transmittance

Table 3. Simulation Parameter

Radiance Parameter	-ab 2 -ad 1000 -as 20 -ar 300 -aa 0.1
Point-in-Time Date	September 21 st (9:00 Am, 12:00 PM)
Occupancy Schedule for Climate-Based Metric	8to6withDST.60min.occ.csv

5.1 DESIGN FLOW

5.1.1 *Floor Height*

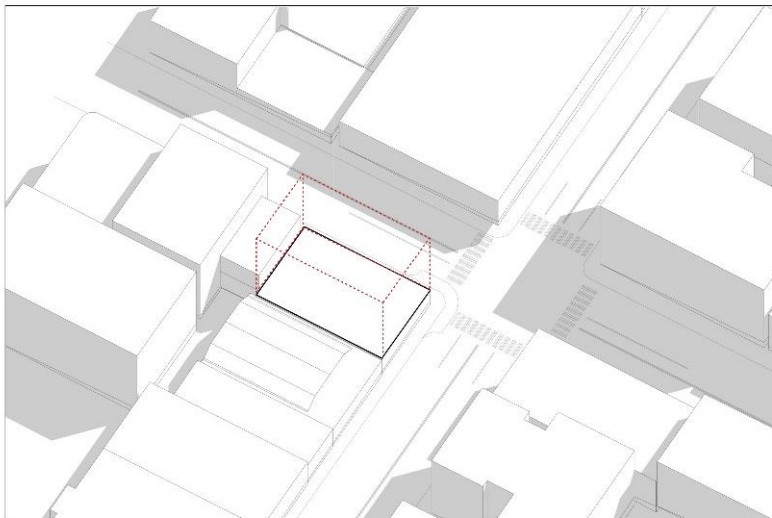


Figure 19. Site Axon

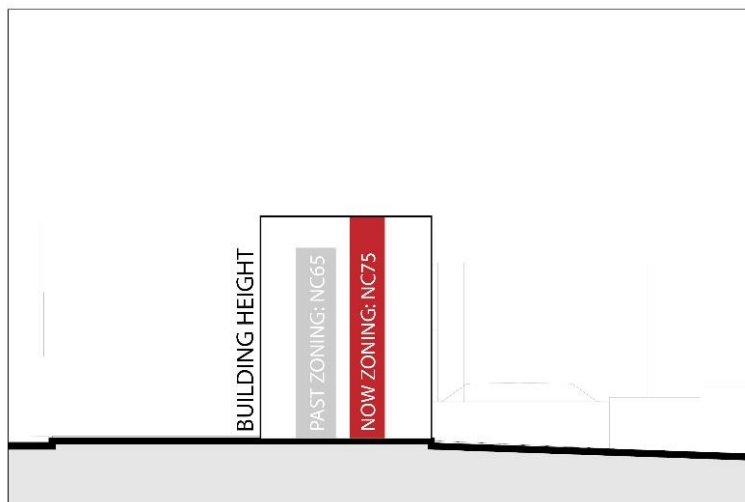


Figure 20. Building Height Limitation

The current zoning height [8] in this building lot is 75'. To focus on upper living floors, the street level floor is set in 14'-0" (13'-0" is the minimum street level height in Seattle Commercial Zones

code [12], and 1'-0" is reserved for structural space). A variety of floor height options are proposed. In the upper living floor, seven floor-floor height options are 8'-0", 8'-6", 9'-0", 9'-6", 10'-0", 10'-6", 11'-0", with the same 1'-0" structure height reserved inside.

(1) Annual-Based Daylight Analysis (UDI)

In some daylight analysis for multiple floors, the top floor and bottom floor is selected as target areas [18]. Two crossed wall partitions are added to simulate the wall partitions. Considering the various floor-to-floor heights and changing the elevation floor height, the lower living floor (the second floor in the building) is selected for simulation.

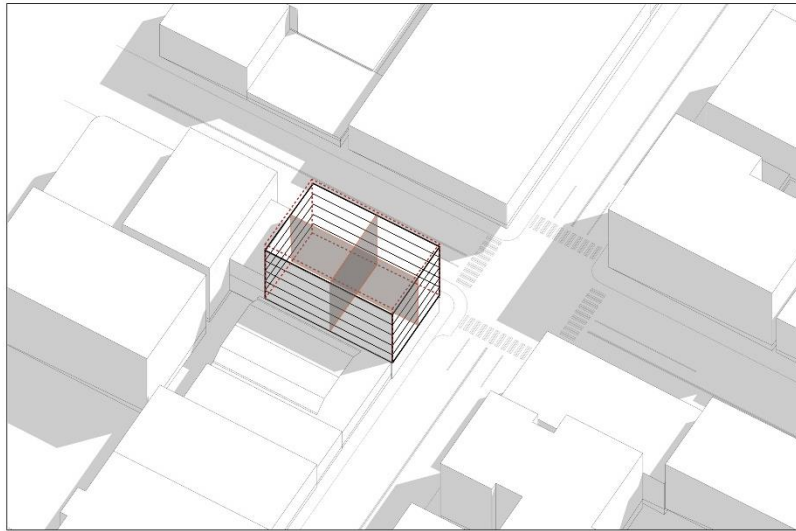


Figure 21. Wall Partition for Height Simulation

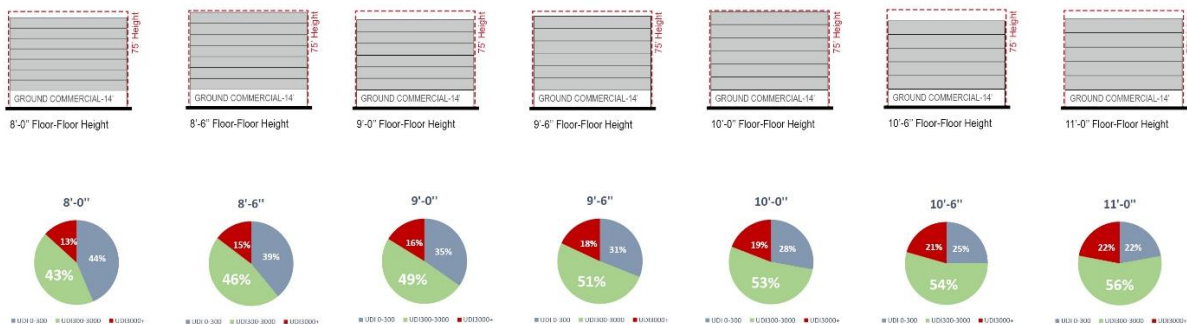


Figure 22. Height Options and UDI Simulation

The UDI simulation shows that with the increasing floor-floor height:

- (a) The percentage of hours in underlit (UDI 0-300lux) decreases;
- (b) The percentage of hours in desirable lit (UDI 300-3000lux) increases;
- (c) The percentage of hours in overlit (UDI >3000lux) increases.

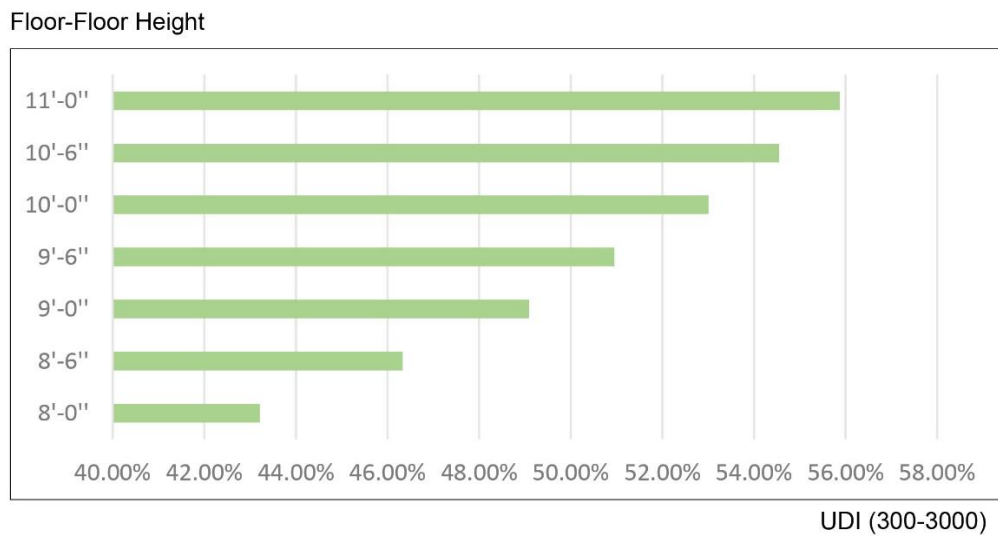


Figure 23. Floor-to-Floor Height and UDI (300-3000lux)

The higher the floor-to-floor height, the greater the percentage of desirable daylight range. However, the percentage of overlit range is slightly increased in the higher floor-to-floor height.

If we only consider the annual daylight performance, it is difficult to determine the exact floor-to-floor height.

(2) Floor Number

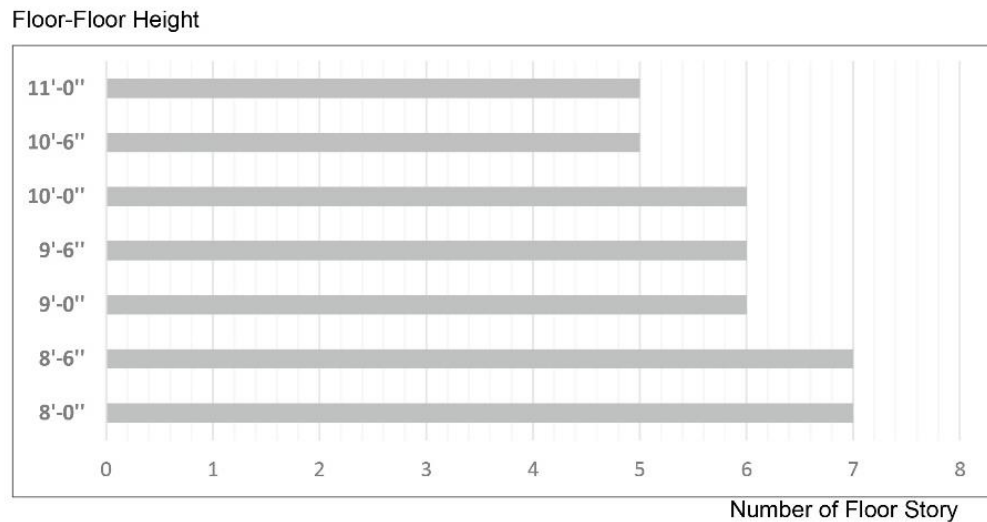


Figure 24. Floor-to-Floor Height and Number of Floor Story

Among the given seven floor-to-floor heights options, the lower floor height accommodates the highest larger number of floors:

- (a) When floor height is 10'-6" or 11'-0", five stories are available;
- (b) When floor height is 9'-0", 9'-6" or 10'-0", six stories are available;
- (c) When floor height is 8'-0" or 8'-6", seven stories are available.

Floor-to-floor height in 8'-0" or 8'-6" brings the maximum seven floors. Because of the reserved 1'-0" height for ceiling space, the actual available floor-to-ceiling heights inside are 7'-0" and 7'-6" respectively. But this interior height is not desirable. The floor-to-floor heights in 10'-6" and 11'-0" bring the higher percentage of desirable daylight range, but those two floor-to-

-floor heights options sacrifice one available floor compared to the height options of 9'-0", 9'-6" and 10'-0".

(3) Height Distribution

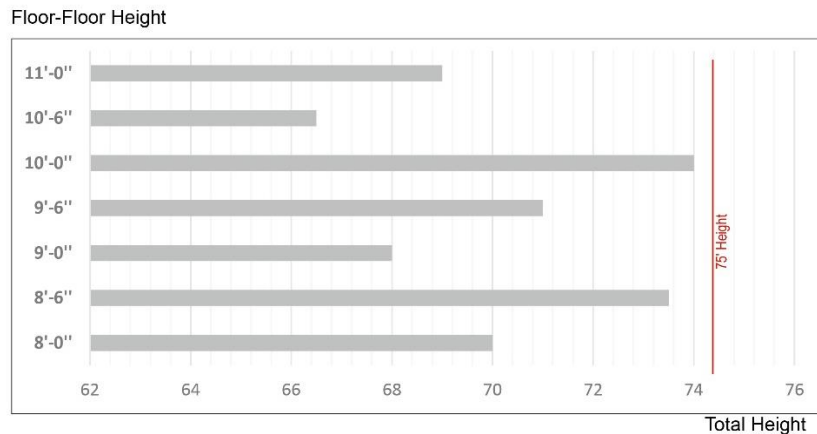


Figure 25. Floor-to-Floor Height and Total Height

Figure 25 shows that how different floor-to-floor height configurations impact the overall building height. Within 75' height limitation, 10'-0" floor-to-floor height spans the overall building height. In other words, from the standpoint of spatial efficiency, if we choose 10'-0", it could realize the maximum building massing in the site. Therefore, 10'-0" is the optimal floor-to-floor height.

5.1.2 Floor Typology

Geometric form defines the primary interaction between building and natural daylight. In 1980, Holl [41] regarded alphabet as an architectural language to determine the high-density building characters. Depending on the main structure and the void space, the buildings could be categorized as "U", "E", "L" and "I" type.

The “U” type is a common configuration: (a) Unlike 3-dimensional building space, the alphabet letter is a 2-dimensional graphic diagram. The ground floor and upper floor have variations in building geometry and floor layout; (b) When buildings have an atrium inside, like “O”, the size of atrium significantly effects the floor layout. A building with a larger-sized atrium leaves less floor depth than the one with a smaller atrium.

In 2015, Dogan [42] divided building typologies into exterior morphology (building massing) and internal organization (indoor floor layout). Except building massing, the floor layout - spatial organizing of room spaces and hallway - could be another type of building form. Floor plans might share the same building massing, but the variation in the circulation/space organization will not impact integrated massing.

This study maintains the same building massing (without a setback or an atrium) and explores the internal floor organization. The floor design includes wall partition, circulation organization (hallway), and building egress (elevator and staircase). Based on the minimum interior dimensions [9-10], it investigates the potential of daylight in developing the interior space.

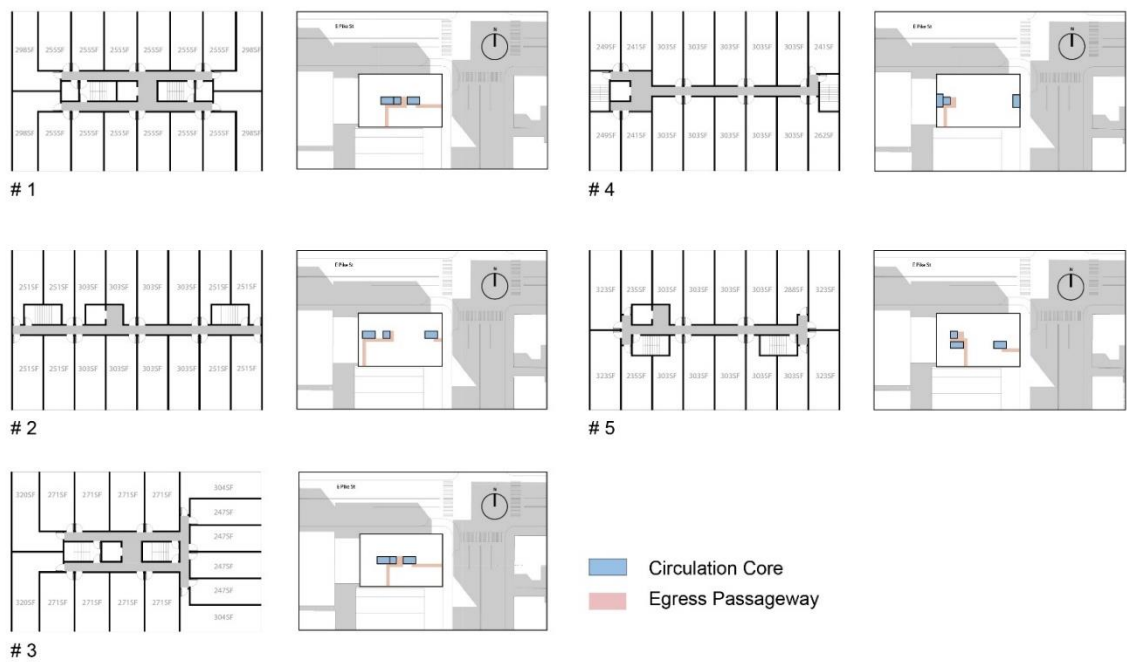


Figure 26. Floor Layout Options

Five floor types are proposed, with a priority of maximizing the number of units. The floor plan incorporates two egress staircases, one elevator, and circulation spaces.

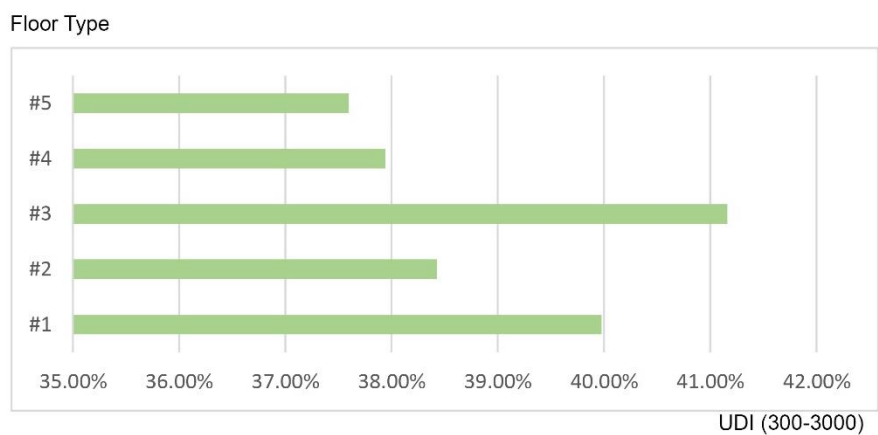


Figure 27. Floor Layout and UDI (300-3000lux)

(1) Floor Layout

Using the minimum floor-ceiling height - 7'-6" [9, 10] and full-glazed window wall, the UDI simulation reveals:

(a) Floor #3 has the greatest value of desirable lit (UDI 300-3000lux), and Floor #1 has the least desirable daylight range among all of the floor types;

(b) Floor #3 has the least underlit issue (UDI 0-300lux);

(c) Floor #3 has the highest overlit value (UDI >3000lux), which potentially causes glare problems. In this typology, the East side is exposed and as the sun is lower in the sky, the sun penetration is deep. If a shading device is added and the window-wall ratio is refined further, the glare issue could be alleviated.

(d). Under 7'-6" height limitation, despite the full-glazed window wall is all used, the desirable ranges (UDI 300-3000lux) in five different floor plans still didn't exceed 42%. It indicates that the minimum 7'-6" floor height is not favorable for designing living units.

Floor Type	Unit Number	Percentage of Desirable Daylight UDI (300-3000)	Percentage of underlit UDI (0-300)	Percentage of overlit UDI (3000+)	Living Area (sq.ft)	Average Unit Size(sq.ft)	Average Unit Width	Average Unit Depth	Corridor Area(sq.ft)	Living Area/Corridor or Area
#1	16	39.98%	48.59%	11.44%	4369.97	273.12	11'-1/4"	23'-1/4"	456.30	9.58
#2	16	38.43%	51.45%	10.14%	4546.16	284.14	11'-3"	26'-11"	375.82	12.10
#3	16	41.16%	43.19%	15.66%	4464.29	279.02	13'-8"	23'-5"	457.72	9.75
#4	16	37.94%	52.00%	10.07%	4507.45	281.72	11'-3"	24'-10"	406.62	11.09
#5	16	37.60%	51.55%	10.85%	4571.24	285.70	11'-3"	26'-11"	350.77	13.03



Figure 28. Daylight Simulation and Spatial Efficiency

(2) Unit Layout

Inside the living units, the wall partition for restroom defines the overall floor depth and width, then it impacts daylight access. Three types of unit layouts and only the open living areas (receiving natural daylight) are applied with simulation nodes; the same types of living units are

grouped as one floor zone. The whole floor's living space is divided into seven different zones by unit layout and orientations as shown in Figure 29.

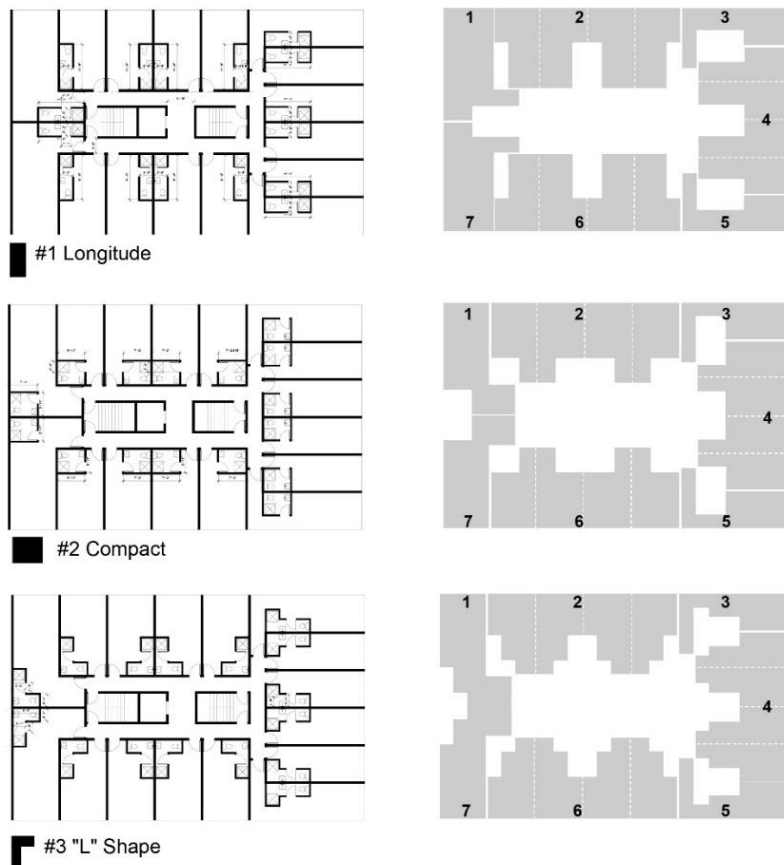


Figure 29. Wall Partitions in the Living Units

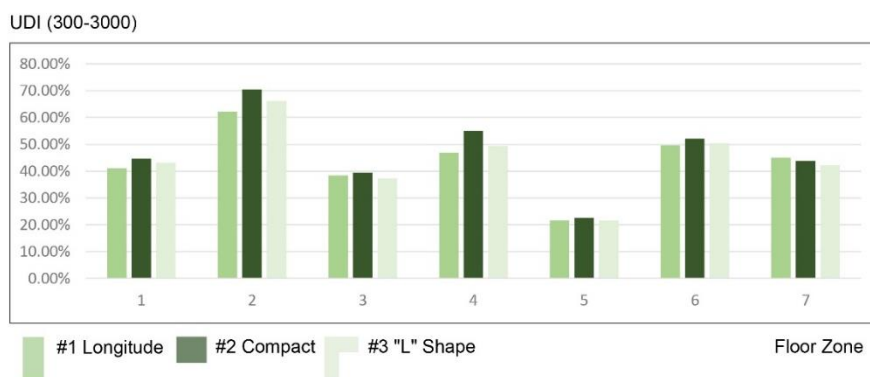


Figure 30. UDI (300-3000lux) and Wall Partitions in the Living Units

The Figure 30 illustrates the annual-based daylight performance (UDI) under different wall partitions:

(a) #3 Compact layout has the highest value of desirable light (300-3000lux), although in zone 7 (Southwest room), it ranks in the second place;

(b) #3 Compact layout has the lowest value of underlit (0-300lux), although it ranks the second place in the zones 3 and 5;

(c) #3 Compact layout has the lowest value of overlit (>3000lux) in floor zones #3 and #5.

The difference between those zones is negligible.

5.1.3 Window-Wall Ratio (WWR)

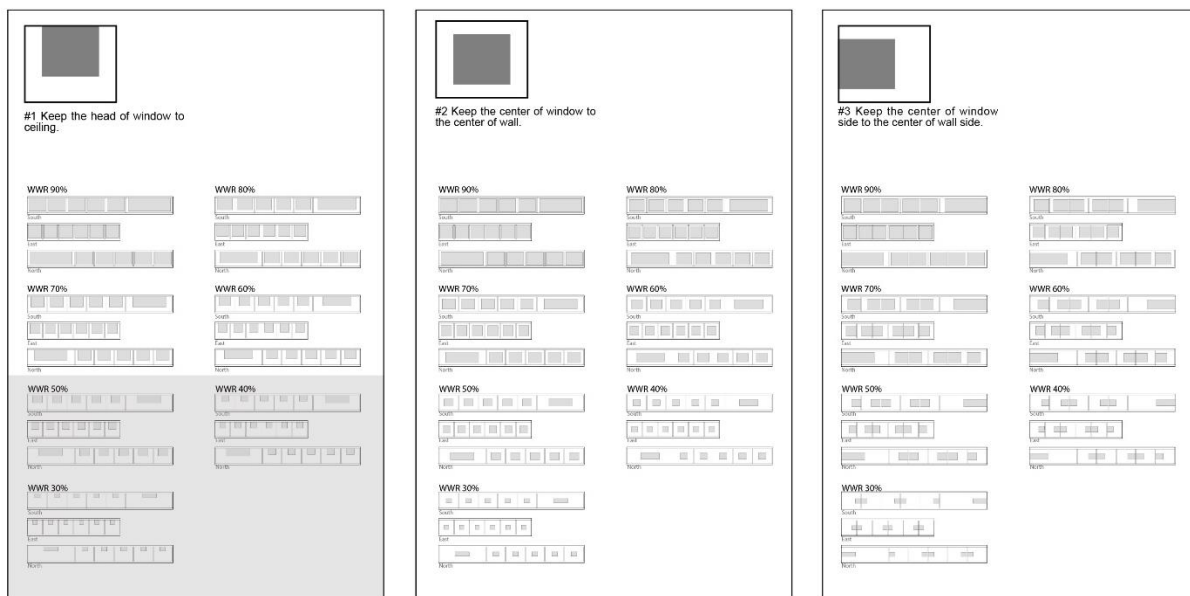


Figure 31. Window-Wall Ratio and Fenestration

Three window-wall ratios (WWR) are considered: (a) WWR Top: the head of the window is attached to the ceiling; (b) WWR Center: the center point of the window is the center point of the exterior wall; (c) WWR Side: the middle point of the window side is attached to the center point

of exterior wall. The related requirement for residential design [11] prescribes the maximum sill height to be 44", considering emergency escape and rescue. When the ratio in WWR Top is under 60%, it fails to meet this requirement, and therefore, such cases are excluded from simulations.

Three same sized rooms oriented in South, North, and East are tested in COMFEN 5.0 for energy consumption. For simplicity, three rooms are modeled in 10' by 11'-8" by 20'-6" (height, width, and Length), and WWR Top 60%-90% are selected.

The established two scenarios are: (1) Inoperable Window (glazing material: Double Clear (Air)); (2) Operable window (90% casement), HVAC (temperature), and Lighting Control (continuous/off).

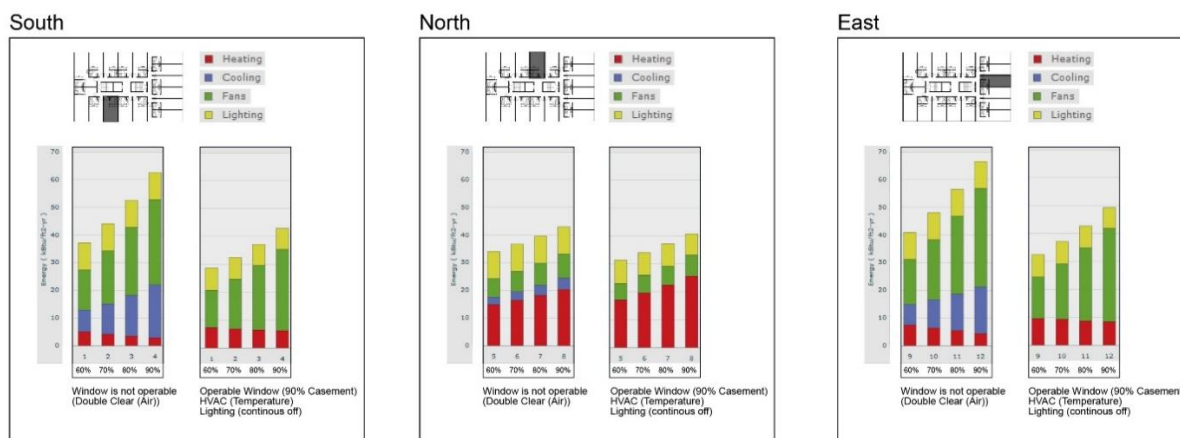


Figure 32. Window-Wall Ratio 60%-90% and Energy Consumption

The impact of increasing WWR when window is inoperable is as follows: (a) In the South-facing room, the fan and cooling loads rises, while the heating consumption drops; (b) In the North-facing room, the heating cooling slightly increases; and (c) In the East-facing room: the heating load drops, but cooling increases.

The impact of increasing WWR, after adding natural ventilation (operable window), HVAC and Lighting control is as follows: (a) In the South-facing room, heating increases but lighting

consumption is lowered, and the use of fans remains consistent; (b) In the North-facing room, heating consumption rises more dramatically; and (c) In the East-facing room, heating rises.

For all of the three rooms, cooling is decreased and lighting consumption uniformly drops as well.

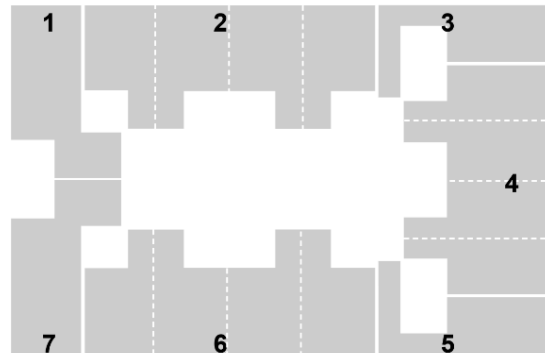


Figure 33. Floor Zones in Simulation

WWR Top	1	2	3	4	5	6	7
WWR 90% Top	37.15%	66.48%	14.61%	50.52%	25.07%	19%	40.47%
WWR 80% Top	35.56%	63.3%	18%	82%	26.06%	62%	9.74%
WWR 70% Top	33.75%	59.9%	61%	89%	29.42%	57%	8.46%
WWR 60% Top	31.62%	52.25%	58.28%	91%	7.90%	60.00%	7.88%
WWR 90% Center	35.08%	52.7%	53%	33%	25.93%	25%	8.98%
WWR 80% Center	31.75%	59%	05%	59%	28.26%	65%	6.09%
WWR 70% Center	28.20%	51.6%	58%	60%	32.22%	73%	3.13%
WWR 60% Center	24.29%	4.67%	72%	6.13%	7.61%	57%	29.38%
WWR 50% Center	19.73%	5.15%	81%	30.60%	3.64%	32%	25.08%
WWR 40% Center	14.48%	25.37%	35%	23.81%	48.19%	5.81%	19.56%
WWR 30% Center	8.59%	14.45%	94%	15.92%	63%	22.90%	13.31%
WWR 90% Side	5.00%	3%	95%	32%	24.48%	31%	9.13%
WWR 80% Side	31.27%	44%	17%	30%	24.23%	54%	6.35%
WWR 70% Side	26.72%	41%	19%	82%	25.34%	98%	2.73%
WWR 60% Side	21.08%	9.12%	13%	4.10%	28.08%	20%	28.02%
WWR 50% Side	15.01%	26.65%	16%	26.86%	31.83%	0.52%	22.05%
WWR 40% Side	10.24%	18.27%	14%	18.76%	4.73%	28.62%	15.37%
WWR 30% Side	6.74%	11.33%	2.45%	11.25%	30.51%	16.78%	9.89%

UDI 300-3000

Figure 34. Window-Wall Ratio and UDI (300-3000lux)

Based on the best percentage of desirable lighting range (UDI 300-3000lux), the WWR for individual floor zones is determined by the highest value (highlighted in bold black font). Zone #3 is categorized into the East-facing zone, as it has window opening toward the East. Zone #5 is categorized as South-facing suite, due to the South window opening.

The conclusions from the WWR analysis are:

(a) There is no significant improvement for daylight when the window is attached to the side of the wall (WWR Side);

(b) The head height of the window is a beneficial factor for improving daylight access. When two windows share the same WWR, the higher the head height of the window, the better desirable daylight for the interior;

(c) The Figure 35 shows that for some floor zones (#3 Northeast, #5 Southeast, and #6 South), a lower value of WWR or different fenestration (WWR center) is more beneficial for daylight; it is due to the potential overlit problem in those spaces;

(d) The value of desirable lit (UDI 300-3000lux) is relatively low in some floor suites (zone #1 Northwest and zone #7 Southwest).

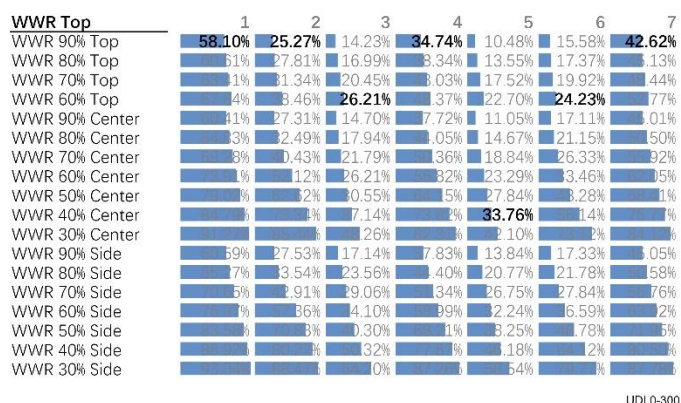


Figure 35. Window-Wall Ratio and UDI (0-300lux)

WWR Top	1	2	3	4	5	6	7
WWR 90% Top	4.75%	8.25%	1.16%	14.74%	15.5%	29.23%	16.91%
WWR 80% Top	3.83%	6.66%	6.83%	12.84%	13.9%	26.01%	15.13%
WWR 70% Top	2.84%	4.87%	8.94%	10.08%	10.06%	22.51%	13.10%
WWR 60% Top	0.74%	1.29%	15.51%	6.72%	9.40%	15.77%	9.35%
WWR 90% Center	4.51%	7.82%	3.77%	13.95%	13.02%	27.64%	16.01%
WWR 80% Center	3.42%	5.92%	2.01%	11.36%	10.7%	23.20%	13.41%
WWR 70% Center	2.52%	4.41%	24.63%	9.04%	9.94%	18.94%	10.95%
WWR 60% Center	1.80%	3.21%	18.07%	7.05%	9.10%	14.97%	8.57%
WWR 50% Center	1.25%	2.23%	12.64%	5.25%	8.52%	11.40%	6.51%
WWR 40% Center	0.73%	1.29%	6.51%	2.37%	18.05%	8.05%	4.67%
WWR 30% Center	0.14%	0.11%	2.80%	1.77%	11.27%	3.98%	2.57%
WWR 90% Side	4.41%	7.74%	3.91%	13.85%	13.68%	27.36%	15.82%
WWR 80% Side	3.46%	6.02%	2.27%	11.30%	13.00%	22.68%	13.07%
WWR 70% Side	2.63%	4.68%	25.75%	8.84%	9.91%	18.18%	10.51%
WWR 60% Side	1.95%	3.52%	19.77%	6.91%	9.68%	14.21%	8.06%
WWR 50% Side	1.41%	2.52%	14.54%	4.93%	9.92%	10.70%	6.00%
WWR 40% Side	0.84%	1.51%	7.54%	3.57%	19.09%	7.26%	4.13%
WWR 30% Side	0.22%	0.20%	3.35%	1.49%	10.95%	3.45%	2.33%

UDI 3000+

Figure 36. Window-Wall Ratio and UDI (>3000lux)

Underlit (UDI 0-300lux) and overlit (UDI >3000lux) values are both used for additional analysis:

- (a) Zone #1 and zone #7 have more underlit issues UDI (0-300lux), with 58.10% and 42.62% respectively;
- (b) For the North-facing zones, #1 and #2 have relatively less overlit issues;
- (c) In the East-facing and South-facing zones (#3, #4, #5, #6, and #7), overlit issue should be addressed further and shading devices are recommended.

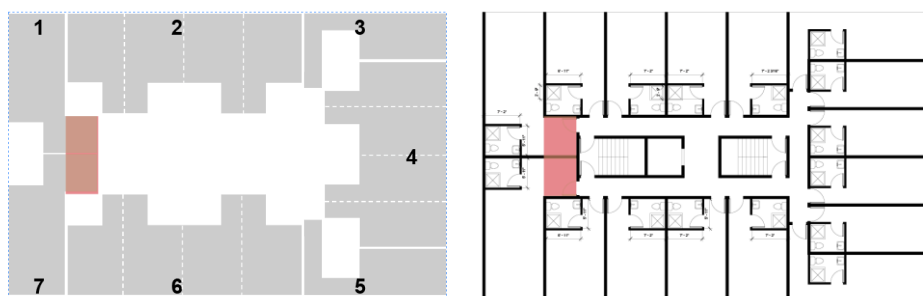


Figure 37. Underlit Analysis for Floor Zones

For floor zone #1 and #7, the underlit problem is mainly due to the entry spaces. In terms of functionality, those spaces are ideal for closet/storage that require low illuminance. In the next step, those two spaces will be maintained in the floor plan, but excluded from the simulation grid.

5.1.4 *Shading Device*

In the previous design decisions, the optimal fenestration and WWR have been determined for individual floor zones. The challenge at this stage is to address the nearly 15%-20% overlit problem ($UDI > 3000\text{lux}$) in the East-facing and South-facing zones. To achieve this, September 21st is chosen as a typical date to design shading devices. As the morning sunlight accesses more in the East-facing room, the point-in-time illuminance at 9:00 AM is used for testing shading effects in the East. The noon sunlight has direct penetration into the South-facing room at 12:00 PM, this point-in-time is chosen for testing hourly illuminance in the South-facing room.

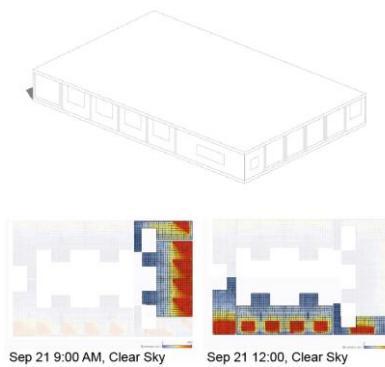


Figure 38. No Shading, Point-in-Time Illuminance

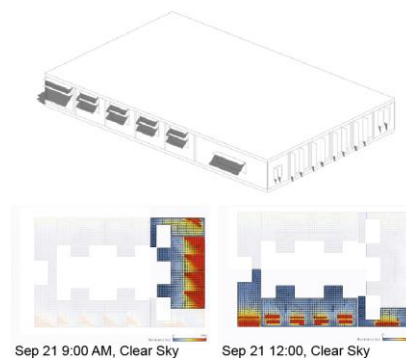


Figure 39. Shading #1, Point-in-Time Illuminance

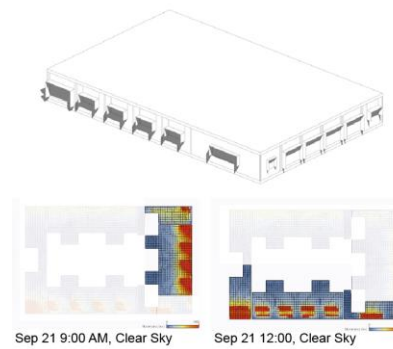


Figure 40. Shading #2, Point-in-Time Illuminance

Table 4. Point-in-Time illuminance comparison

Floor Zone	#1	#2	#3	#4	#5	#6	#7
No shading-9:00 AM	417.30	592.68	3718.21	9059.25	5835.47	3635.07	4839.67
No shading-12:00 PM	476.66	672.58	715.96	701.14	6250.81	7680.03	10453.20
Shading #1-9:00 AM	405.42	575.63	2240.21	6592.94	3026.48	2157.28	2902.89
Shading #1-12:00 PM	477.27	672.03	684.75	645.73	3451.11	4884.60	5600.32
Shading #2-9:00 AM	447.60	634.17	1724.00	5549.13	4119.75	3306.94	4876.40
Shading #2-12:00 PM	478.90	674.70	671.58	640.18	4618.31	5043.62	7976.30

(Sep 21st, Clear Sky, Point-in-Time Illuminance, unit: lux)

By using simulation-based tool (Diva in Rhino-Grasshopper), two shading strategies were tested and the optimal shading depth is determined for individual windows.

(a) Shading #1: For the South-facing room, two separate horizontal panels are placed near the window with a light shelf at the top. To maintain the view from the interior to exterior, the lower panel is placed at the height of 6'-8". For the East-facing room, two vertical panels are placed at the window's South side and midline of the window. The length of each vertical panel is equal to window height. The shading depth (either 1'-0", or 1'-6") depends on the floor zones.

(b) Shading #2: For South-facing and East-facing windows, it uses integrated shading devices (combined with horizontal and vertical shading panels). The top of shading device is placed at the

height of 6'-8" for the view access as well. The shading depth is 1'-0", 1'-6", or 2'-0", correlating with the depth of the floor zones.

The false-color map and illuminance value are both utilized to represent shading effects. The graphic results show that both shading devices can block portions of sunlight at 9:00 AM and 12:00 PM. For the East-facing rooms, Shading #2 has a better performance in lowering the average illuminance at 9:00 AM, and Shading #1 is more efficient for shading in the South-facing rooms.

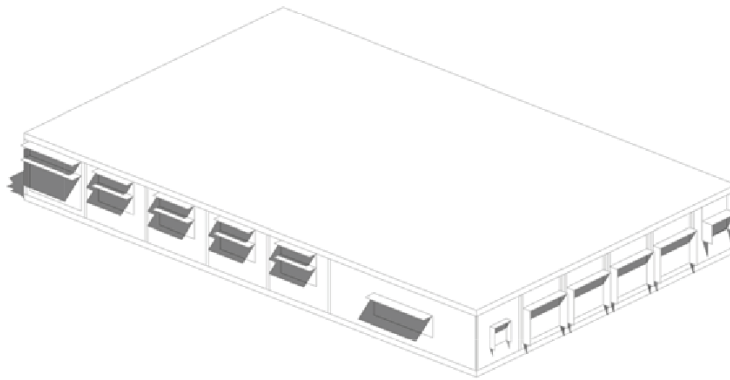


Figure 41. Shading #3

Therefore, the design decision for final shading strategy (Shading #3) is to use Shading #1 for the South-facing zones and choose Shading #2 for the East-facing zones.

5.1.5 *Visual Comfort*

(1) Daylight Glare Probability (DGP)

In DGP simulation, four perspectives (Northeast, East, Southeast, South) are selected in the South-facing and East-facing zones. The start point of view is 10'-0" perpendicularly away to the window; the view height is all set in 6'-0" (the length of the camera for perspective is 15). To incorporate light resource from the two sides of windows, the view directions in the Northeast-facing and Southeast-facing zones follow the interior corner-to-corner diagonal line. Corresponding to the

point-in-time setting in previous shading design, September 21st 9:00 AM is selected for the East-facing zone; September 21st 12:00 PM is selected for South-facing zone.

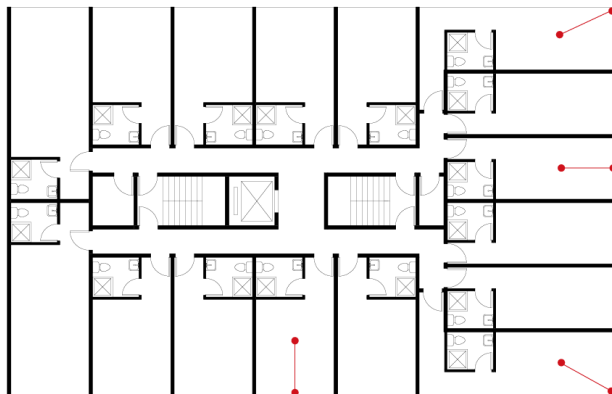


Figure 42. View Setting for DGP

DGP simulation uses hemispherical fisheye image to represent the occupant's perspective view. Combined with false-color visualization, the characters of luminance distribution - starting from a single viewpoint to the endpoint of the view - are analyzed.

No Shading

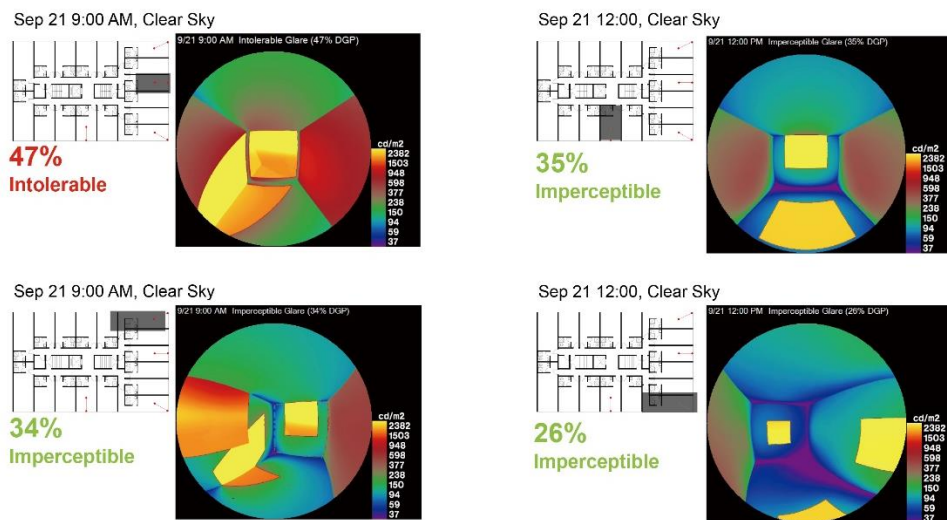


Figure 43. No Shading, DGP Simulation

Shading #1

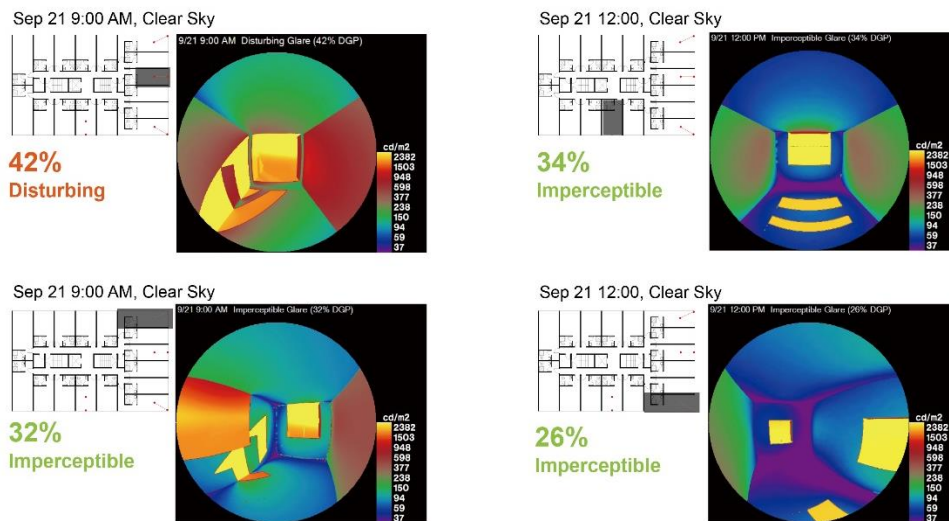


Figure 44. Shading #1, DGP Simulation

Shading #2

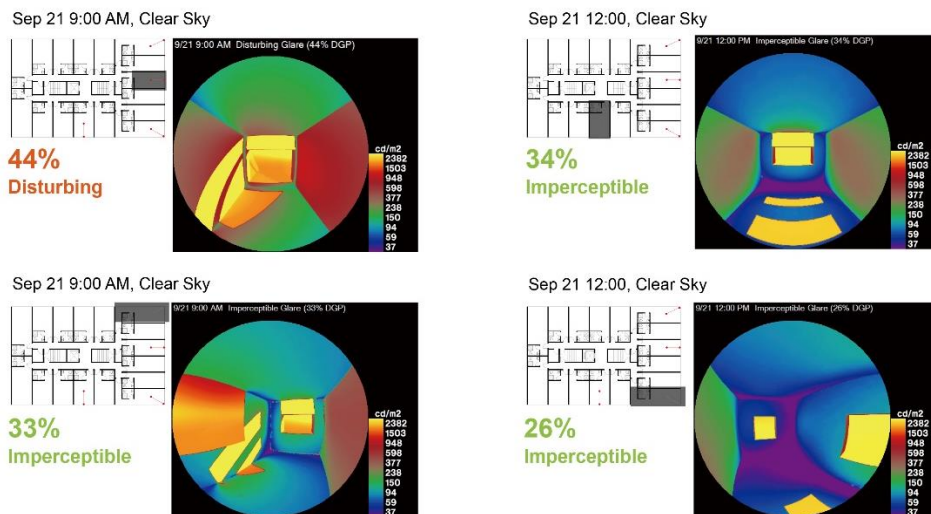


Figure 45. Shading #2, DGP Simulation

The three sets of DGP simulation show the glare scenarios: No Shading, Shading #1, and Shading #2. When there is no shading device, the glare is “intolerable” (DGP 47%) in East-facing room, and the glare in three other rooms are “imperceptible”. After Shading #1 is added, the glare in the East-facing room is alleviated from “intolerable” (DGP 47%) into “disturbing” (DGP 42%).

Meanwhile, the DGP value in Northeast-facing and the South-facing room is slightly decreased. Despite the DGP in the Southeast-facing room stays consistent, the false-color image indicates that the overall luminance drops compared to the No Shading scenario. After Shading #2 is added, it is also effective in alleviating the DGP from “intolerable” (DGP 47%) into “disturbing” (DGP 44%). Although the DGP in the other three perspectives remains in the level of “imperceptible”, the shading device still has shading effects according to the false-color images.

The results show that the presence of shading devices could not only effectively reduce glare issue in the East-facing room from “intolerable” to “disturbing” but also alleviate visual discomfort in three other rooms by lowering the overall luminance. Furthermore, it is worthwhile to note that whether outdoor shading devices are added or not, there is still some penetration of direct sunlight in three DGP simulation scenarios. The next step is to consider an internal shading device, roller shade fabrics, so as to achieve a more suitable visual comfort in the East South facing rooms.

Annual based daylight UDI 300-3000 lux	1	2	3	4	5	6	7
No shading	43.24%	66.33%	57.97%	50.46%	48.33%	59.67%	47.80%
Shading 1-horizontal	43.11%	66.34%	58.88%	50.31%	47.22%	57.70%	46.38%
Shading 2-integrated	43.20%	66.38%	59.47%	51.19%	46.32%	58.90%	49.02%
Shading 3-auto 300-3000	43.36%	62.28%	62.89%	48.04%	9.45%	4.10%	30.76%
Shading 3-auto 300-4000	43.34%	62.27%	63.79%	45.21%	23.64%	43.18%	38.46%
Shading 3-auto 300-5000	43.36%	62.27%	62.96%	48.76%	11.94%	16.06%	32.44%
Shading 3-auto 2000-3000	43.36%	62.27%	63.80%	39.92%	9.16%	3.98%	30.55%
Shading 3-auto 3000-4000	43.42%	62.33%	63.93%	48.62%	11.84%	16.26%	32.19%

Figure 46. UDI (300-3000lux) for Shading Strategies in Floor Zones

When interior shading is added, different thresholds are tested in the setting of automated glare control (Diva for Rhino) with desirable daylight range (UDI 300-3000lux). Figure 47 shows how various thresholds impact the percentages of desirable daylight range (UDI 300-3000lux) in individual floor zones. The automated interior shades could block sunlight, but it also results in over-shading. Compared to those scenarios without automated roller shades, the value of (UDI 300-3000lux) increases in zone #3 (Northeast-facing room). There is an undesirable over-shading

effect in zone #5, and the over-shading problem also appears in other floor zones. The threshold 300-4000lux has the least effect of over-shading. But for most of the South-facing and East-facing rooms (except zone #3), it lowers the percentages of desirable daylight range (UDI 300-3000lux) throughout the whole year. The interior shading device does not deploy till illuminance reaching 4000lux, whereas UDI starts penalizing with the values above 3000lux. However, considering the flexibility of movement in a residential setting, it is acceptable to operate the shading device automation in a high setting. Considering the potential glare caused by direct sunlight, automated shading is an effective approach to be deployed by individuals, and further analysis is necessary to test its effectiveness in preventing the annual glare.

(2) Annual Daylight Glare Probability (Annual DGP)

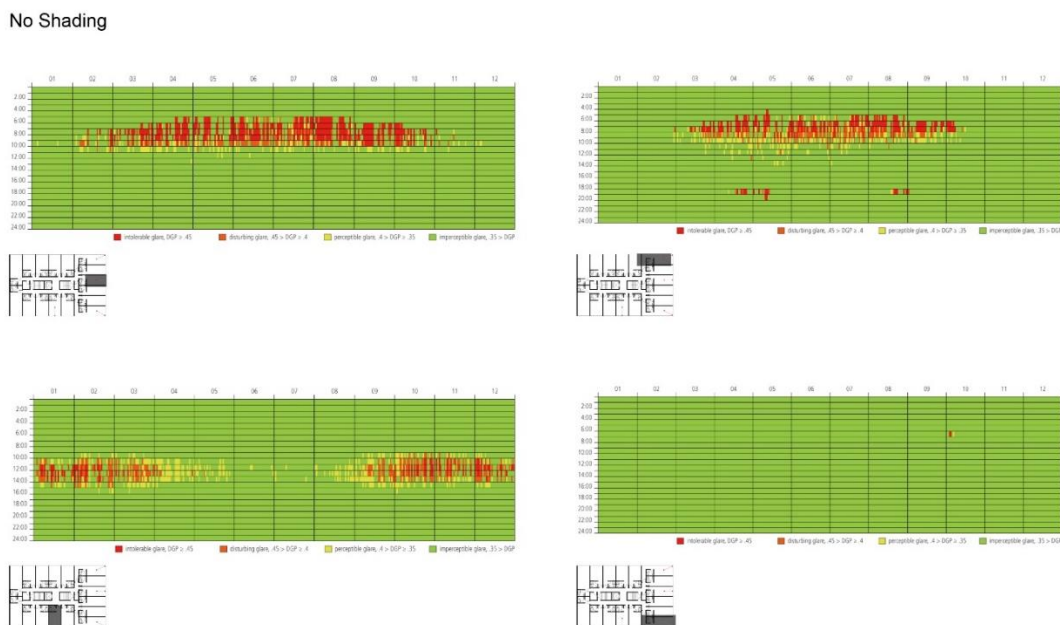


Figure 47. No Shading, Annual DGP for Different Units in a Floor

Shading #1

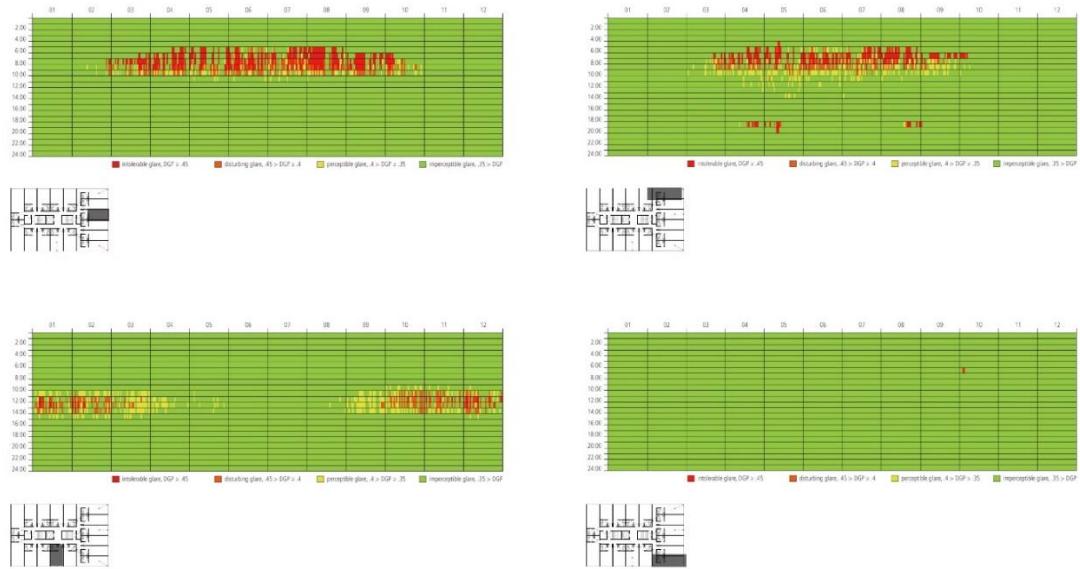


Figure 48. Shading #1, Annual DGP for Different Units in a Floor

Shading #2

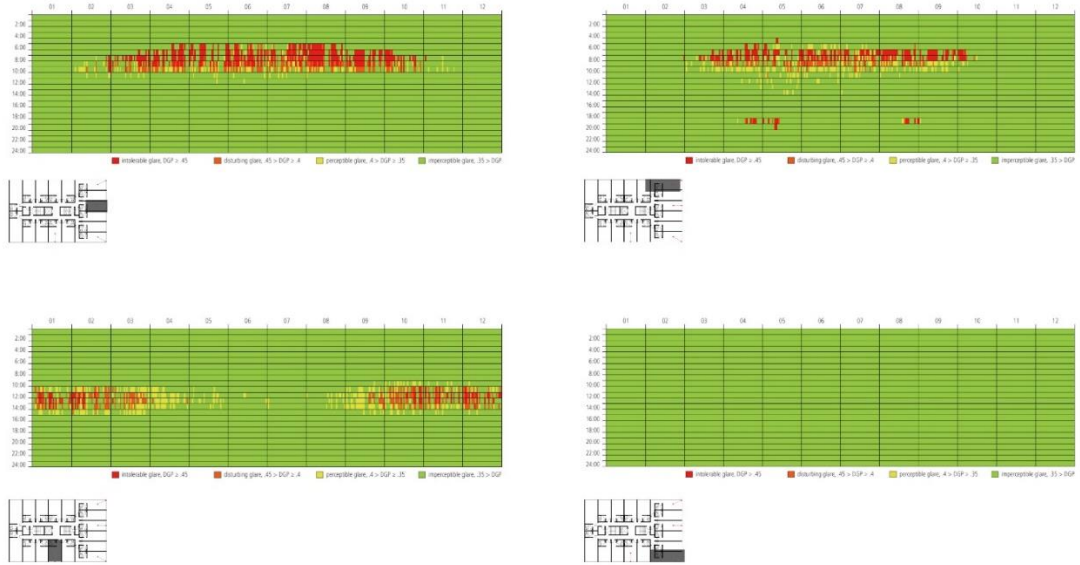


Figure 49. Shading #2, Annual DGP for Different Units in a Floor

Shading #3

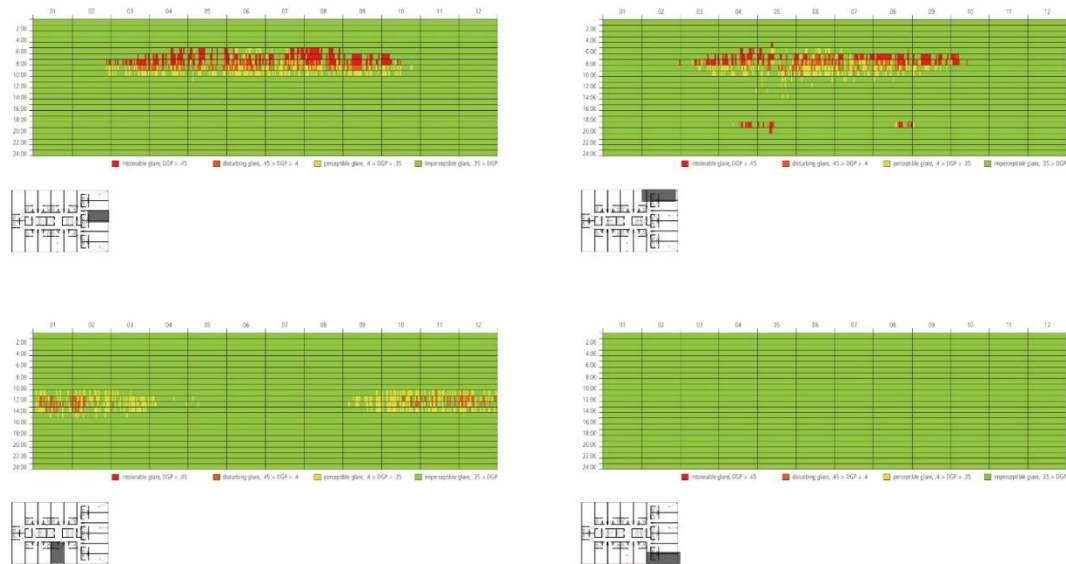


Figure 50. Shading #3 with Automated Roller Shades (off: 300 lux, on: 4000 lux), Annual DGP

Different Units in a Floor

The Figure 50 shows Annual DGP for the No Shading, Shading #1, Shading #2 and Shading #3 (automate shading, threshold: 300-4000lux). When there is no shading, glare mainly occurs during morning hours from March to October in the East-facing window. In the South-facing unit, the glare issue appears during the afternoon hours between September and March. In the Northeast-facing window, glare issue appears from March to October between mornings to noon. In the Southeast-facing room, there is no glare issue. The graphic also indicates that glare issue is prevalent in particular time points (during the night of April, May and August). The surrounding buildings are not modeled in this simulation setting.

For three shading strategies, Shading #1 and Shading #2 both lower the glare throughout the entire year. Shading #3 (automated interior shades) works more effectively in decreasing the annual glare issue. It also indicates that some glare issues, especially “Intolerable” level glare, persists at limited time frames throughout the year.

Since the glare (DGP and Annual DGP) is based on individual viewpoints (position and field of view), the result only represents the glare prediction based on the four established perspectives. Even if there is no glare in the Southeast-facing room, the glare might appear in other positions and viewpoints.

5.1.6 *Floor Layout*

The final floor plan incorporates the previous design decisions as well as basic furniture layout. The minimum interior dimension from the Seattle Building Code [9] is used to test the design rationality. The code prescribes “the habitable spaces except for a kitchen, shall not be less than 7’-0” in any plan dimension”. Unlike the International building Code Handbook’s interpretation on this - “7’-0” diameter circle”, Seattle Building code takes 7’-0” as minimum dimension throughout all corners in the required area. In Figure 51, the yellow color highlights the whole habitable area (living area) and a rectangle, 7’-0” by 7’-0”, is outlined. There is a lot of extra space in the South-facing and North-facing rooms to satisfy the minimum interior dimension. But for the East-facing room, due to the deep room depth, the interior areas don’t have too much extra space that satisfies the 7’-0” minimum dimension. The red color hatch covers the hallway space that cannot satisfy 7’-0” minimum dimension either. For the Northeast, Southwest, Northeast and Southeast-facing room, the hallway spaces take much more area than other floor zones, especially the entry space in Northeast and Southeast-facing room is not functional no matter for daylight or storage space.

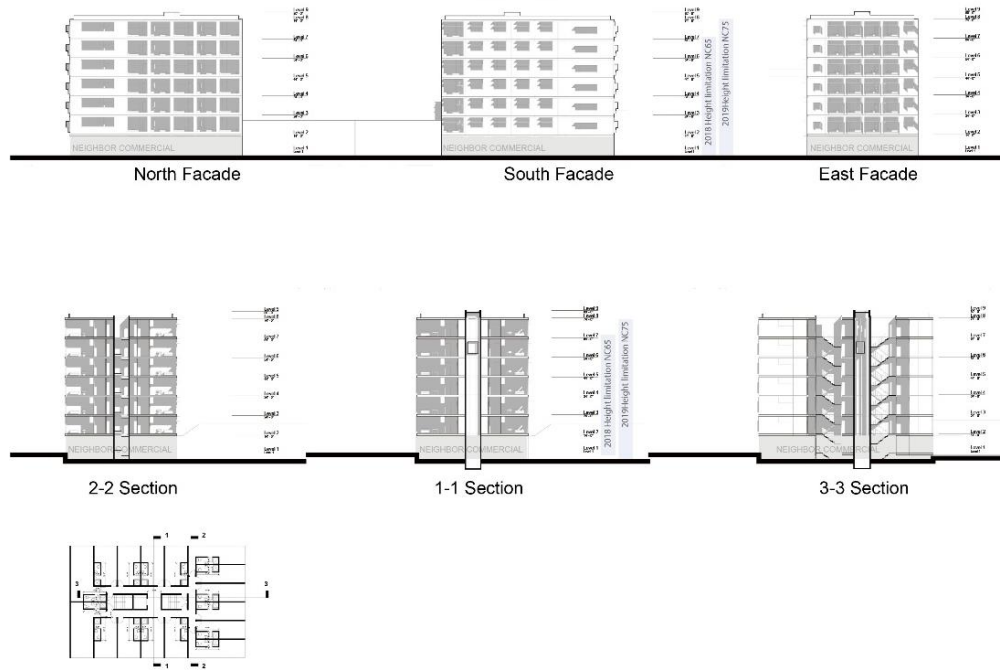


Figure 52. Building Façade and Main Sections

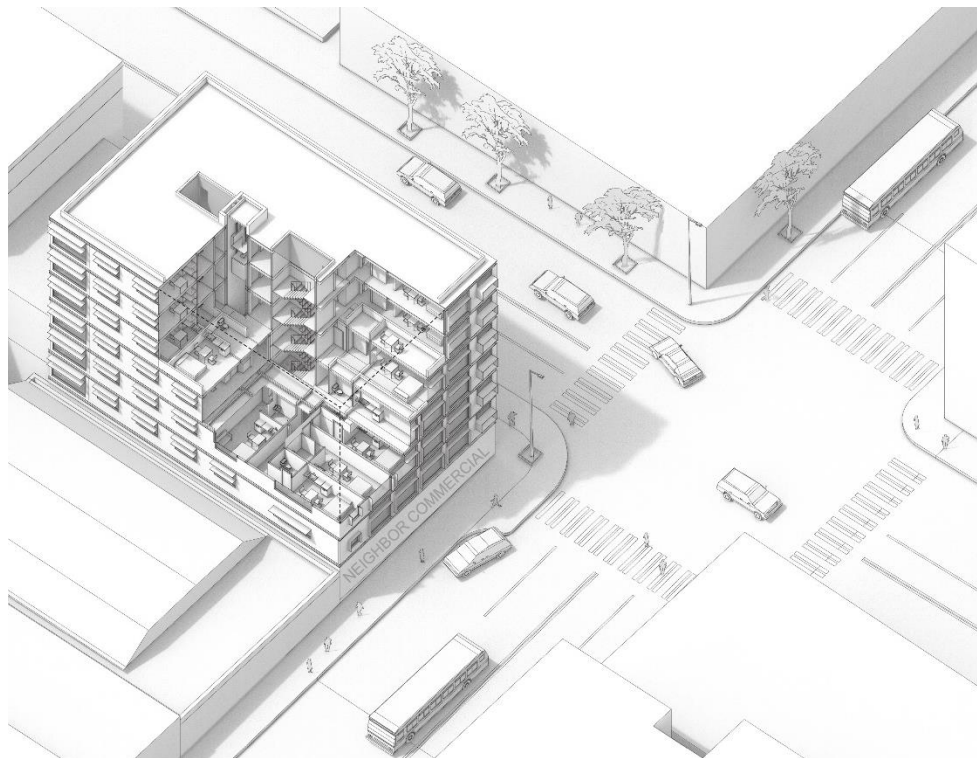


Figure 53. Sectional Axon



Figure 54. Street View

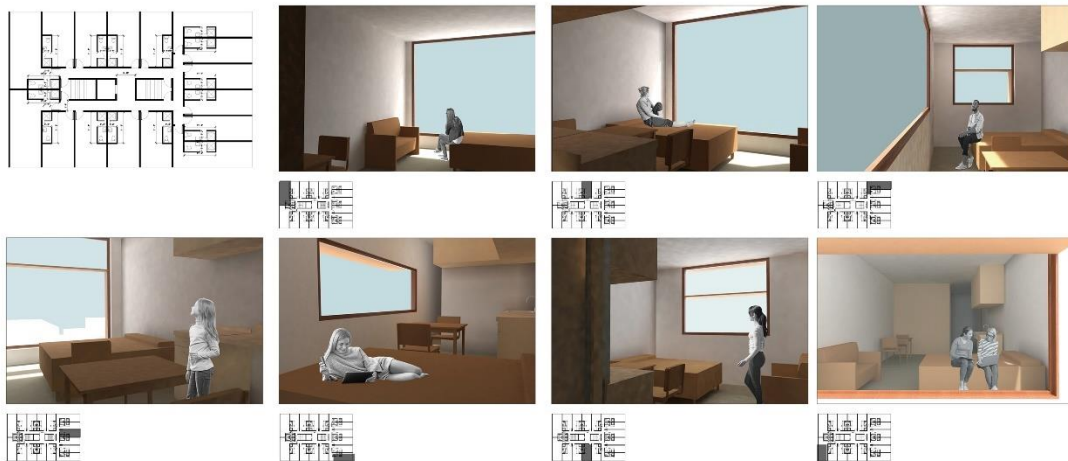


Figure 55. Interior Perspectives

Chapter 6. CONCLUSIONS

6.1 DISCUSSION

The discussion highlights the key points in the occupant-centric design workflow when daylight availability and visual comfort are prioritized.

(1) Building Height

The building height impacts the daylight availability in a given unit. Seven floor-to-floor height options are tested: 8'-0", 8'-6", 9'-0", 9'-6", 10'-0", 10'-6", and 11'-0". This study shows that with the increasing floor-to-floor height, the percentage of desirable daylight percentage (UDI 300-3000lux) becomes higher. Meanwhile, the percentage of overlit (UDI >3000lux) increases and percentage of underlit (UDI 0-300lux) range drops. The result appears that the higher floor-to-floor height brings the more desirable daylight and less underlit problems, given the potential overlit issues could be addressed further. However, the high floor-to-floor height negatively impacts the available number of floors. The total building height works as another constraint in design. With 10'- 0" floor-to-floor height, the entire building height reaches 74' (under the 75' limitation [8]) and it brings maximum building massing.

(2) Building Orientation

In a North-South orientated building lot, this study investigates the typical room orientations with five different floor plans in Seattle. As some floor plans don't have East-facing rooms, the simulation result only shows the daylight in the North and the South respectively. Due to the existing construction in the West of the site, no window openings are available in the West-facing orientation in this study.

In a simulation that uses 7'-6" as floor-to-floor height [9,10] and full-glazing windows, the simulation plane is divided into the North and the South. The annual-based daylight analysis (UDI) shows that the North-facing rooms receive a higher percentage of desirable daylight (UDI 300-3000lux) and underlit range (UDI 0-300lux) than the South-facing rooms. Compared to the North-facing rooms, the rooms in the South receives more abundant sunlight, along with overlit (illuminance that exceeds 3000lux). Therefore, shading controls are necessary to improve the percentage of desirable daylight range (UDI 300-3000lux) for the South-facing rooms.

(3) Floor Layout

The simulation results show that the percentage of desirable daylight range (UDI300-3000lux) in all five floor types didn't exceed 41%, and the percentage range of underlit is between 43% and 52% (without any shading device). The minimum 7'-6" height is not favorable for receiving daylight in living units. The optimal floor is #3 (shown in Figure 26). This typology contains North, South and East facing rooms, with the highest 41% of desirable daylight range (UDI 300-3000lux) and the least 43% of underlit range (UDI 0-300lux). Although the percentage of overlit range (UDI >3000lux) ranks highest as well, it is because the East window openings bring more sunlight into the floor space. With the maximum average room width (13' - 8") and minimum average room depth (23' - 5"), this typology has more integrated interior spaces. Considering the number of units in all five floor types are all sixteen, choosing floor type #3 means that the desirable daylight during the entire year will be ensured, despite the fact that its spatial efficiency may not be optimum.

(4) Window-Wall Ratios (WWR)

Window openings are the primary light sources for a sidelight living unit. Three WWR ratios are considered: (a) WWR Top (the head of the window is attached to the ceiling); (b) WWR Center (the center point of the window is the center point of the exterior wall); (c) WWR Side: the middle

point of the window side is attached to the central point of the wall. Based on the percentage of desirable daylight range (UDI 300-3000), the result of WWR study that higher window location is the most beneficial approach to improve interior daylight. When shading device is not employed, the WWR in different orientations are determined by the simulation result (desirable daylight range (UDI 300-3000lux), Figure 34). The North, East, and Southwest facing rooms need 90% WWR (Top); the rooms in the Northeast-facing require a lower WWR (Top) - 60%; and the 40% WWR (Center) is recommended for South-facing rooms.

(5) Shading Strategies

September 21st (equinox) is chosen to design shading devices. The shading devices in the East-facing and South-facing orientations are determined by the best shading effects in lowering the hourly illuminance at 9:00 AM and 12:00 PM respectively. The final shading strategy adopts horizontal shading panels for the South-facing rooms; and the integrated shading device (combined with vertical and horizontal shading panels) is used for East-facing rooms. Both shading devices leave the light shelf at the height of 6'-8" for the purpose of interior-to-exterior view.

(6) Visual Comfort

Glare metrics (DGP, annual DGP) are used to test shading effects based on the four chosen occupants' views with the same view settings. The instantaneous DGP and annual DGP simulations illustrate that all shading devices could lowering luminance in the fisheye images. It is worthwhile to note that there is still some direct sun penetration in the interior spaces, no matter what kind of outdoor shading devices are selected. In this case, roller shades are recommended for improving visual comfort further. The annual DGP shows that deploying roller shades reduces the glare issue effectively on a yearly basis. However, such an interior shading device may cause overshading effects in the desirable daylight range (UDI 300-3000lux), if not adequately operated.

(7) Glazing Specification

For maximizing desirable daylight range, the façade design is primarily driven by the optimal WWR values and most of living units adopt high WWR. In this case, using multi-glazing (or energy - efficient glazing) window will balance the heating loss and daylight availability. As natural ventilation improves living comfort, the operable window will be favorable. However, as heating has more significant effects on living comfort than cooling in Seattle, multi-glazing is prioritized over the operable window.

6.2 DESIGN GUIDELINES

After previous analysis and discussion, a series of design guideline is finalized for Seattle multi-family design:

(1) Floor-to-Floor Height: 10'-0" is the optimal floor-to-floor height (with 1'-0" height for structural space) in the NC75 (Neighborhood Commercial, 75'-0" height limitation). The minimum 7'-6" is not favorable in residential design.

(2) Room Orientation: For a rectangle building lot, if more orientations has the window openings, the overall floor area receives more desirable daylight (UDI 300-3000lux), as well as excess sunlight (UDI >3000lux).

(3) Unit Depth: During the entire year, the South-facing rooms have more significant overlit issues (UDI >3000) and less underlit issues (UDI 0-300lux) than the North-facing rooms. Given the same unit width, minimizing the unit depth in the North and extending the unit depth in the South could improve the overall daylight distribution, if overlit area around window region is acceptable.

(4) Fenestration: with the same interior wall materials, placing the window at the side of the wall do not significantly improve desirable daylight range (UDI 300-3000lux). The most effective way to bring daylight into interior is to place the head of the window attach to the ceiling.

(5) Window Specification: multi-glazing window is favorable for minimizing the heating loss; the operable window is beneficial for dropping the cooling load.

(6) Shading Strategies: both the South and the East facing rooms need shading devices (the West is excluded in this study), and the room in the Southeast or the Northeast corners need shading more. For the exterior shading, the horizontal shading device is more efficient in decreasing hourly illuminance in the South-facing orientation; the integrated shading device works better for the East-facing orientation. If the outdoor shading is not feasible because of limited building setback, interior roller shades is another shading approach.

(7) Glare Control: interior roller shading is the most efficient shading strategy in decreasing annual-based glare issues. Movable shading device operation can be customized for visual comfort with different individual preferences and site contexts.

6.3 OCCUPANT-CENTRIC DESIGN FLOW IN RESIDENTIAL BUILDINGS

Main issues in residential daylight design are the varying target illuminance for different tasks, age and gender [40] and lack of daylight metric for residential building. Due to those reasons, annual-based desirable daylight range (UDI 300-3000lux) is introduced to guide the daylight design process. The overlit range (UDI >3000lux) indicates potential glare areas that need shading strategies and glare control; and underlit range (UDI 0-300lux) provides recommendations on floor layouts.

As a simulation metric, UDI has its merits and shortcomings. The value of UDI percentages are derived from illuminance values throughout the year, it is an accumulated value. It is powerful

as a single metric, but the data is compressed. Generating both false-color imagery and UDI value for all design proposals can be overwhelming. This study, hence, selects the desirable daylight range and represent this value consistently. In this way, it provides quick evaluations of alternatives throughout the design process. False-color imagery is utilized at selected design phases (shading device design) to supplement the UDI calculations.

Using the same time point setting in shading design and glare analysis minimizes the variables in two different measurements (illuminance and luminance) and connects horizontal node-based illuminance to the hemispherical glare perception.

6.4 FURTHER STUDY

This study introduced an occupant-centric daylight design flow for residential building and used daylight simulation to support design decisions. By discussing daylight in parallel with other design constraints, the design flow supports informed decision making. The emphasis on the value of desirable daylight range (UDI 300-3000lux) simplified the interpretation of daylight simulation without interrupting a typical design flow. The occupant-centric design flow demonstrates the capacity of simulation data in developing building spaces. As shading design only considered the sun position in the September 21st (9:00 AM, 12:00 PM), other time points need to be tested further for a more specific shading strategy. The DGP results only show the glare perception generated from the chosen four view directions/positions. Due to the flexibility of occupant activities/schedule, more view settings with computational simulation will be needed as well.

Except for building height, the rest of simulation does not incorporate surrounding buildings. Therefore, this study only shows the daylight design for developing floor plates. The daylight performance in different floors still need to be studied further. The indoor roller shades with different thresholds are useful to address the daylight difference between the top floor and bottom

floor. This study could be further expanded to higher UDI thresholds, further research is needed to determine whether people may be willing to tolerate higher lighting values in residential settings.

BIBLIOGRAPHY

- [1] “Overview 2018_FINAL.” FMINET. Accessed May 6th, 2019.
https://www.fminet.com/wp-content/uploads/2018/01/Overview2018_FINAL.pdf
- [2] “As Apartments Are Shrinking, Seattle Tops New York with the Smallest Rentals in the U.S.” Rentcafe. Accessed May 20th, 2019. <https://www.rentcafe.com/blog/rental-market/real-estate-news/us-average-apartment-size-trends-downward/>
- [3] “Seattle DPD - Seattle's Comprehensive Plan, Readers Guide, Jan 2005.” Seattle.Gov. Accessed January 1st, 2019.
www.seattle.gov/dpd/cs/groups/pan/@pan/documents/web_informational/dpdd016661.pdf
- [4] “Seattle OPCD - Citywide Detail Permit Report Q4 2016.” Seattle.Gov. Accessed November 2th, 2018.
www.seattle.gov/dpd/cs/groups/pan/@pan/documents/web_informational/dpdd016661.pdf
- [5] “Most and Least Expensive States to Build a Home.” gobankingrates. Accessed January 20th, 2019. <https://www.gobankingrates.com/investing/real-estate/most-expensive-cheapest-states-to-build-house/#3>
- [6] “Multifamily Market Research, Seattle 2018.” Kidder Mathews. Accessed February 2nd, 2019. <https://kidder.com/>
- [7] “City of Seattle, Generalized Zoning.” Seattle.Gov. Accessed June 2nd, 2019.
www.seattle.gov/dpd/Research/gis/webplots/smallzonemap.pdf
- [8] “Directors_Report_MHA_Citywide.” Seattle.Gov. Accessed April 10th, 2019.
www.seattle.gov/Documents/Departments/HALA/Policy/Directors_Report_MHA_Citywide.pdf
- [9] “2015 Seattle Building Code.” Seattle.Gov. Accessed November 10th, 2018.
[www.seattle.gov/sdci/codes/codes-we-enforce-\(a-z\)/building-code](http://www.seattle.gov/sdci/codes/codes-we-enforce-(a-z)/building-code)
- [10] “2015 Seattle Fire Code.” Seattle.Gov. Accessed November 10th, 2018.
[www.seattle.gov/sdci/codes/codes-we-enforce-\(a-z\)/fire-code](http://www.seattle.gov/sdci/codes/codes-we-enforce-(a-z)/fire-code)
- [11] “Seattle SDCI Tip #303A - Common Seattle Residential Code Requirements.” Seattle.Gov. Accessed April 2nd, 2019. www.seattle.gov/DPD/Publications/CAM/cam303A.pdf
- [12] “Seattle DCI - Seattle's Commercial Zones Summary.” Seattle.Gov. Accessed April 20th, 2019.
<https://www.seattle.gov/Documents/Departments/SDCI/Codes/CommericalZoningSummary.pdf>

- [13] “Gen 2 Nova brochure final.” Otis Elevator Company. Accessed April 22nd, 2018. <https://files.otis.com/otis/en/in/contentimages/Gen%202%20Nova%20brochure%201Oct%202018>.
- [14] “HOW SEATTLE KILLED MICRO-HOUSING.” Sightline. Accessed November 22nd, 2018. <https://www.sightline.org/2016/09/06/how-seattle-killed-micro-housing/>
- [15] “HOW SEATTLE KILLED MICRO-HOUSING, AGAIN.” Sightline. Accessed December 22nd, 2018. <https://www.sightline.org/2017/03/20/how-seattle-killed-micro-housing-again/>
- [16] Reinhart, Christoph, and Stephen Selkowitz. "Daylighting—Light, Form, and People." *Energy and Buildings* 38, no. 7 (2006): 715-17.
- [17] Reinhart, Christoph, John Mardaljevic, and Zack Rogers. "Dynamic Daylight Performance Metrics for Sustainable Building Design," *Leukos* 3, no.1 (2006), 7-31.
- [18] Tregenza, P., and J. Mardaljevic. "Daylighting Buildings: Standards and the Needs of the Designer." *Lighting Research & Technology* 50, no. 1 (2018): 63-79.
- [19] Reinhart, Christoph. "Opinion: Climate-based Daylighting Metrics in LEEDv4 – A Fragile Progress." *Lighting Research & Technology* 47, no. 4 (2015): 388.
- [20] Galasiu, Anca D., and Christoph F. Reinhart. "Current Daylighting Design Practice: A Survey." *Building Research & Information* 36, no. 2 (2008): 159-74.
- [21] “BREEAM UK New Construction 2014.” BREEAM. Accessed June 8, 2019. <https://www.breeam.com/>
- [22] “LEED v4 for Building Design and Construction.” US Green Building Council (USGBC). Accessed June 8, 2019. <https://new.usgbc.org/leed#rating>
- [23] “Assessment Standard for Green Building GB/T50378-2019.” Ministry of Housing and Urban-Rural Development of People’s Republic of China (MOHURD). Accessed June 8, 2019. http://www.mohurd.gov.cn/wjfb/201905/t20190530_240717.html
- [24] “WELL Building Standard v1.” WELL. Accessed June 8, 2019. <https://www.wellcertified.com/>
- [25] Nabil, A., and J. Mardaljevic. "Useful Daylight Illuminance: A New Paradigm for Assessing Daylight in Buildings." *Lighting Research & Technology* 37, no. 1 (2005): 41-57.
- [26] Reinhart, Christoph F., and Oliver Walkenhorst. "Validation of Dynamic RADIANCE-based Daylight Simulations for a Test Office with External Blinds." *Energy and Buildings* 33, no. 7 (2001): 683-97.
- [27] “Annual Daylighting Performance Metrics, Explained.” *Architectural Lighting*. Accessed February 25th, 2018. https://www.archlighting.com/technology/annual-daylighting-performance-metrics-explained_o

- [28] Andersen, Marilyne, John Mardaljevic, Nicolas Roy, and Jens Christoffersen. "Climate-based Daylight Performance: Balancing Visual and Non-visual Aspects of Lighting Input", Proceedings CISBAT. Lausanne, Switzerland, (2011): 385-389.
- [29] Mardaljevic, John, Marilyne Andersen, Nicolas Roy, and Jens Christoffersen. "Daylighting metrics: is there a relation between useful daylight illuminance and daylight glare probability." Proceedings of Building Simulation and Optimization, Loughborough, UK. (2012): 189-96
- [30] Dogan, Timur, and Ye Chan Park. "A Critical Review of Daylighting Metrics for Residential Architecture and a New Metric for Cold and Temperate Climates." *Lighting Research & Technology* 51, no. 2 (2018): 206-30.
- [31] Boyce, Peter R. *Human Factors in Lighting*. Boca Raton: CRC Press/Taylor & Francis Group, 2014.
- [32] Reinhart, Christoph F., and Jan Wienold. "The Daylighting Dashboard – A Simulation-based Design Analysis for Daylit Spaces." *Building and Environment* 46, no. 2 (2011): 386-96.
- [33] Jakubiec, J. Alstan, and Christoph F. Reinhart. "The 'adaptive Zone' – A Concept for Assessing Discomfort Glare throughout Daylit Spaces." *Lighting Research & Technology* 44, no. 2 (2011): 149-70.
- [34] Pierson, Clotilde, Jan Wienold, and Magali Bodart. "Discomfort Glare Perception in Daylighting: Influencing Factors." *Energy Procedia* 122 (2017): 331-36.
- [35] Wienold, Jan, and Jens Christoffersen. "Evaluation Methods and Development of a New Glare Prediction Model for Daylight Environments with the Use of CCD Cameras." *Energy and Buildings* 38, no. 7 (2006): 743-57.
- [36] Jones, Nathaniel L., and Christoph F. Reinhart. "Effects of Real-time Simulation Feedback on Design for Visual Comfort." *Journal of Building Performance Simulation* 12, no. 3 (2018): 343-61.
- [37] Jakubiec, J. Alstan, and Christoph F. Reinhart. "A Concept for Predicting Occupants' Long-Term Visual Comfort within Daylit Spaces." *Leukos* 12, no. 4 (2015): 185-202.
- [38] Mardaljevic, John, Marilyne Andersen, Nicolas Roy, Jens Christoffersen. "Daylighting metrics for residential buildings" Proceedings of the 27th Session of the CIE, Sun City, South Africa, 01, no.1 (2010): 93-11
- [39] Dogan Timur, and Ye Chan Park. "A New Framework for Residential Daylight Performance Evaluation." Proceedings of Building Simulation 2017, San Francisco, USA, (2017): 389-97.

- [40] Peters, Terri, and Ted Kesik. "Daylight Simulation for Multi-Unit Residential Buildings: Occupant-Centered Approaches to Assessment for Cold and Temperate Climates." *Lighting Research & Technology*, (2018), 1-10.
- [41] Holl, Steven. *The Alphabetical City*. New York, NY: Princeton Architectural Press, 1987.
- [42] Dogan, Timur, Emmanouil Saratsis, and Christoph Reinhart. "The Optimization Potential of Floor-Plan Typologies in Early Design Energy Modeling." *Proceedings of Building Simulation 2015, Hyderabad, India*, (2015), 1853-860.

APPENDIX A

Floor-to-Floor Height and UDI Simulations

Floor-Floor Height	UDI 0-300	UDI300-3000	UDI3000+
8'-0"	43.58%	43.21%	13.21%
8'-6"	39.01%	46.33%	14.66%
9'-0"	34.71%	49.09%	16.20%
9'-6"	31.02%	50.95%	18.08%
10'-0"	27.88%	53.01%	19.11%
10'-6"	24.88%	54.55%	20.57%
11'-0"	22.14%	55.87%	21.99%

Floor Layout Options and UDI Simulations

Floor Type	Orientation	Underlit UDI (0-300)	Acceptable UDI(300-	Overlit UDI(3000+
#1	N	58.18%	36.61%	5.21%
#1	S	38.99%	43.34%	17.67%
#1	Average	48.59%	39.98%	11.44%
#2	N	56.82%	38.53%	4.66%
#2	S	46.07%	38.32%	15.62%
#2	Average	51.45%	38.43%	10.14%
#3	N	49.55%	41.06%	9.39%
#3	S	36.82%	41.26%	21.93%
#3	Average	43.19%	41.16%	15.66%
#4	N	59.65%	36.08%	4.32%
#4	S	44.34%	39.85%	15.81%
#4	Average	52.00%	37.94%	10.07%
#5	N	60.92%	34.44%	4.63%
#5	S	42.18%	40.75%	17.07%
#5	Average	51.55%	37.60%	10.85%

Unit Layout Options and UDI Simulation

Unit Layout #1-Longitude			
#1-Floor Zone	#1-underlit UDI 0-300	1#-Desirable UDI 300-3000	1#-Overlit UDI 3000+
1	52.70%	41.16%	6.14%
2	27.41%	62.18%	10.41%
3	9.29%	38.42%	52.29%
4	34.58%	46.84%	18.58%
5	6.61%	21.60%	71.79%
6	17.64%	49.67%	32.69%
7	34.60%	44.91%	20.49%
Restroom #2-Compact			
#2-Floor Zone	#2-underlit UDI 0-300	2#-Desirable UDI 300-3000	2#-Overlit UDI 3000+
1	49.19%	44.57%	6.24%
2	18.64%	70.38%	10.98%
3	10.59%	39.48%	49.93%
4	26.42%	55.08%	18.50%
5	7.37%	22.57%	70.06%
6	11.65%	52.01%	36.34%
7	35.42%	43.79%	20.79%
Restroom #3-L shape			
#3-Floor Zone	#3-underlit UDI 0-300	3#-Desirable UDI 300-3000	3#-Overlit UDI 3000+
1	50.67%	43.08%	6.25%
2	23.36%	66.16%	10.48%
3	10.65%	37.30%	52.05%
4	31.92%	49.28%	18.80%
5	7.26%	21.57%	71.17%
6	15.73%	50.32%	33.95%
7	37.01%	42.24%	20.75%

WWR Top and Window Configuration

WWR Top	Window Figures	1	2	3-Front	3-Side	4	5-Side	5-Front	6	7
WWR 90% Top	Sill Height	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
	Window Top Height	9	9	9	9	9	9	9	9	9
	Dimensions (x*y)	10.455*8.1	10.455*8.1	26.25*8.1	8.175*8.1	8.175*8.1	8.175*8.1	26.25*8.1	10.455*8.1	10.455*8.1
WWR 80% Top	Sill Height	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
	Window Top Height	9	9	9	9	9	9	9	9	9
	Dimensions (x*y)	9.293*7.2	9.293*7.2	23.333*7.2	7.267*7.2	7.267*7.2	7.267*7.2	23.333*7.2	9.293*7.2	9.293*7.2
WWR 70% Top	Sill Height	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
	Window Top Height	9	9	9	9	9	9	9	9	9
	Dimensions (x*y)	8.132*6.3	8.132*6.3	20.417*6.3	6.358*6.3	6.358*6.3	6.358*6.3	20.417*6.3	8.132*6.3	8.132*6.3
WWR 60% Top	Sill Height	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6
	Window Top Height	9	9	9	9	9	9	9	9	9
	Dimensions (x*y)	6.97*5.4	6.97*5.4	17.5*5.4	5.45*5.4	5.45*5.4	5.45*5.4	17.5*5.4	6.97*5.4	6.97*5.4
WWR 50% Top	Sill Height	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
	Window Top Height	9	9	9	9	9	9	9	9	9
	Dimensions (x*y)	5.808*4.5	5.808*4.5	14.583*4.5	4.542*4.5	4.542*4.5	4.542*4.5	14.583*4.5	5.808*4.5	5.808*4.5
WWR 40% Top	Sill Height	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
	Window Top Height	9	9	9	9	9	9	9	9	9
	Dimensions (x*y)	4.647*3.6	4.647*3.6	14.583*4.5	3.633*3.6	3.633*3.6	3.633*3.6	14.583*4.5	4.647*3.6	4.647*3.6
WWR 30% Top	Sill Height	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
	Window Top Height	9	9	9	9	9	9	9	9	9
	Dimensions (x*y)	3.485*2.7	3.485*2.7	8.75*2.7	2.725*2.7	2.725*2.7	2.725*2.7	8.75*2.7	3.485*2.7	3.485*2.7

WWR Center and Window Configuration

WWR Center	Window Figures	1	2	3-Front	3-Side	4	5-Side	5-Front	6	7
WWR 90% Center	Sill Height	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
	Window Top Height	8.55	8.55	8.55	8.55	8.55	8.55	8.55	8.55	8.55
	Dimensions (x*y)	10.455*8.1	10.455*8.1	26.25*8.1	8.175*8.1	8.175*8.1	8.175*8.1	26.25*8.1	10.455*8.1	10.455*8.1
WWR 80% Center	Sill Height	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
	Window Top Height	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1
	Dimensions (x*y)	9.293*7.2	9.293*7.2	23.333*7.2	7.267*7.2	7.267*7.2	7.267*7.2	23.333*7.2	9.293*7.2	9.293*7.2
WWR 70% Center	Sill Height	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35
	Window Top Height	7.65	7.65	7.65	7.65	7.65	7.65	7.65	7.65	7.65
	Dimensions (x*y)	8.132*6.3	8.132*6.3	20.417*6.3	6.358*6.3	6.358*6.3	6.358*6.3	20.417*6.3	8.132*6.3	8.132*6.3
WWR 60% Center	Sill Height	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
	Window Top Height	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
	Dimensions (x*y)	6.97*5.4	6.97*5.4	17.5*5.4	5.45*5.4	5.45*5.4	5.45*5.4	17.5*5.4	6.97*5.4	6.97*5.4
WWR 50% Center	Sill Height	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25
	Window Top Height	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75
	Dimensions (x*y)	5.808*4.5	5.808*4.5	14.583*4.5	4.542*4.5	4.542*4.5	4.542*4.5	14.583*4.5	5.808*4.5	5.808*4.5
WWR 40% Center	Sill Height	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
	Window Top Height	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
	Dimensions (x*y)	4.647*3.6	4.647*3.6	11.667*3.6	3.633*3.6	3.633*3.6	3.633*3.6	11.667*3.6	4.647*3.6	4.647*3.6
WWR 30% Center	Sill Height	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15
	Window Top Height	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85
	Dimensions (x*y)	3.485*2.7	3.485*2.7	8.75*2.7	2.725*2.7	2.725*2.7	2.725*2.7	8.75*2.7	3.485*2.7	3.485*2.7

WWR Side and Window Configuration

WWR Side	Window Figures	1	2	3-Front	3-Side	4	5-Side	5-Front	6	7
WWR 90% Side	Sill Height	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
	Window Top Height	8.55	8.55	8.55	8.55	8.55	8.55	8.55	8.55	8.55
	Dimensions (x*y)	10.455*8.1	10.455*8.1	26.25*8.1	8.175*8.1	8.175*8.1	8.175*8.1	26.25*8.1	10.455*8.1	10.455*8.1
WWR 80% Side	Sill Height	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
	Window Top Height	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1
	Dimensions (x*y)	9.293*7.2	9.293*7.2	23.333*7.2	7.267*7.2	7.267*7.2	7.267*7.2	23.333*7.2	9.293*7.2	9.293*7.2
WWR 70% Side	Sill Height	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35
	Window Top Height	7.65	7.65	7.65	7.65	7.65	7.65	7.65	7.65	7.65
	Dimensions (x*y)	8.132*6.3	8.132*6.3	20.417*6.3	6.358*6.3	6.358*6.3	6.358*6.3	20.417*6.3	8.132*6.3	8.132*6.3
WWR 60% Side	Sill Height	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
	Window Top Height	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
	Dimensions (x*y)	6.97*5.4	6.97*5.4	17.5*5.4	5.45*5.4	5.45*5.4	5.45*5.4	17.5*5.4	6.97*5.4	6.97*5.4
WWR 50% Side	Sill Height	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25
	Window Top Height	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75
	Dimensions (x*y)	5.808*4.5	5.808*4.5	14.583*4.5	4.542*4.5	4.542*4.5	4.542*4.5	14.583*4.5	5.808*4.5	5.808*4.5
WWR 40% Side	Sill Height	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
	Window Top Height	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
	Dimensions (x*y)	4.647*3.6	4.647*3.6	11.667*3.6	3.633*3.6	3.633*3.6	3.633*3.6	11.667*3.6	4.647*3.6	4.647*3.6
WWR 30% Side	Sill Height	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15
	Window Top Height	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85
	Dimensions (x*y)	3.485*2.7	3.485*2.7	8.75*2.7	2.725*2.7	2.725*2.7	2.725*2.7	8.75*2.7	3.485*2.7	3.485*2.7