DAYLIGHTING AS A SYNTHESIS TOOL IN THE EARLY DESIGN STAGE

An Integrated Daylighting Design Procedure for Configuration of Buildings

Junghwa Kim Suh
May 2013

Submitted towards the fulfillment of the requirements for the Doctor of Architecture Degree.

School of Architecture
University of Hawai'i

Doctorate Project Committee
Hyung-June Park, Chairperson
Eileen Peppard
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We certify that we have read this Doctorate Project and that, in our opinion, it is satisfactory in scope and quality in fulfillment as a Doctorate Project for the degree of Doctor of Architecture in the School of Architecture, University of Hawai'i at Manoa.

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ABSTRACT

This study proposes an integrated design procedure with natural light for the development of the optimal configurations of buildings to achieve a satisfactory visual comfort level. Natural light has both psychological and physiological benefits to humans, which makes it a critical design factor for the built environment. There is a growing need of its effectual integration in the architectural design process today. The application of daylighting in current design practice has focused on an analysis of lighting quality in a single building during the post design phase. In order to satisfy and improve the level of visual comfort in a building, the investigation on how multiple buildings affect the lighting quality to each other should be conducted.[1] A systematic procedure of daylighting integration with multiple buildings in the early stage of design will allow designers to configure the design of multiple buildings for optimizing visual comfort. The proposed approach provides a procedure to integrate daylighting as a synthesis tool in the early architectural design stage to inform the relationship between buildings and visual comfort at an urban-scape. The procedure consists of the application of a 3D volumetric boundary and the design rules for configurations of buildings with various computational tools. The boundary is established through *Climatic Envelope*[2], which clarifies an environmentally conscious design setting for architects. The design rules are developed and articulated through experimental research in 1) orientation of building growth pattern, 2) placement of buildings and 3) building form and size under two dominant sky conditions; clear and overcast. The integrated design procedure with natural light is investigated through two site studies, located in Honolulu, Hawaii and Seattle, Washington where two dominant sky conditions are represented. The intention of developing this procedure is to assist architects in the development of the initial configuration of buildings with the goal of optimizing visual comfort for users.

[1] Steffy, 2002.
[2] Mark DeKay, 2010.

1. INTRODUCTION

1.1 Prelude

Natural light is one of the fundamental factors in environmental design which significantly affects users' satisfaction with allowing basic human activities, creating spatial experience and revealing the form of a space. Lighting design is necessary for providing visual comfort for human tasks and activities with the appropriate illuminance level, which is the density of light on a surface. The research shows that the integration of natural light in architectural design provides psychological and physiological health benefits to humans. It is also one of the most effective ways for the reduction of energy use and bringing economic benefits which aligns with the growing need of environmental sustainability today.[1]

The integration of natural light has been developed as one of environmental analysis that evaluates lighting quality during daytime.[2] Various strategies for effective daylighting implementation on building facade designs have been explored and analyzed rigorously. The goal of these strategies is to provide visual comfort within an interior space. However, these strategies are only effective after the building design is completed due to the knowledge of factors such as a building's location, orientation, and size of openings and shades. Therefore, the existing daylighting design guide from literatures informs a single facade design in post design stage.

Ralph Knowles (1981) and G.Z. Brown & Mark DeKay (2001) have introduced the concept of envelope with natural light. Natural light envelopes are based on the idea of constructing a 3D volumetric boundary of an urban-scape that assures solar access and ambient lighting in multiple buildings. The concept of natural light envelopes introduces the potential for an integration of natural light within a holistic approach, due to its ability of embracing the dynamic dimensions of daylighting's continuously changing nature, and the broad perspective of urban-scape.[3] Its synthetic implementation on an urban site allows designers to examine visual comfort in multiple buildings. Therefore, the integration of daylighting into the design of buidings gains more weight would be more effective in the early design stage when it is considered at an urban-scape.[4] This research will explore the initial configurations of buildings using the 3D volumetric boundary to achieve optimum/average visual comfort. This investigation utilizes daylighting as a main design-driving factor in the early architectural design phase with various computational tools.

[1] International Energy Agency (IEA), 2000.
[2] Caldas, 2008.
[3] Rakha & Nassar, 2010.
[4] Capeluto, Design Tools for Solar and Daylight Access in Urban Design, 68.

1.2 Scope of Research

Through literature review, daylighting analysis, simulation, evaluation, and synthesis of multiple buildings, this research provides the procedure to configure buildings in a given site for optimizing buildings' average visual comfort level. The proposed integrated design procedure with natural light is composed of two major components; the construction of 3D volumetric boundary and design rules for configurations of buildings under two dominant sky conditions. First, 3D volumetric boundary, *Climatic Envelope* (DeKay, 2010) is explored. Since it is a composite of solar and daylight envelopes, the buildings in *Climatic Envelope* are satisfied with both solar access and ambient lighting. The envelope is constructed from a modeling tool based on the established construction steps by Mark DeKay (2010). Secondly, the buildings inside of the envelope will be developed, based upon reaching a satisfactory visual comfort level. Experimental research on the illuminance level of two buildings is conducted with the variations of 1) building orientation, 2) placement of buildings and 3) building form under two dominant sky conditions, clear and overcast. Throughout this investigation, a shadow study of buildings from Ecotect, as well as an illuminance simulation from DesignBuilder will be conducted to understand the critical factors of daylighting impact on the relationship of multiple buildings for the purpose of achieving a visually comfortable illuminance level. From the outcomes of the experimental research, basic design rules of configurations of buildings are generated.

The procedure will be applied in the redesign of an urban-scape in Honolulu, Hawaii and Seattle, Washington. Based on the sites' locations and latitudes, a 3D volumetric boundary and dominant sky condition will be determined. The design rules for the configuration of buildings under the clear sky condition will be applied in the redesign of the site in Honolulu, and the rules under the overcast sky condition will be applied to the site in Seattle. The outcomes of the shadow studies and comparisons of theilluminance levels will provide additional insights on the configurations of buildings in different sky conditions.

Consequently, this research will redefine analysis-based daylighting integration in the current architectural design process as a design-driving factor and urban form generating synthesis tool in the early design stage with the goal of optimizing average visual comfort.

1.3 Organization of Dissertation

This dissertation is presented in seven chapters, including the bibliography. The first chapter provides the delineation of research and identifies the study's goal and scope.

The second chapter offers general information about daylighting design in architecture. It discusses a historical overview of parameters, principles and current design strategies of daylighting in the architectural design. It also describes current daylighting design metrics and tools to understand how daylighting is implemented in the architectural design process.

Chapter three presents the exemplary studies on the influence and use of daylighting design in the modification of a building and the synthesis of urban form. The studies demonstrate the impact of daylighting in the design of a single building and multiple buildings in urban-scape. It also proposes how daylighting can be integrated into the early design stage to inform the building design and its relationship among multiple buildings.

In chapter four, the synthesis-based daylighting design framework and an integrated procedure for the configuration of buildings is established through the implementation of *Climatic Envelope* (DeKay, 2010) and design rules for configurations of buildings. This chapter will investigate relationships between natural light and multiple buildings through a synthetic application of daylighting. The procedure is presented in a systematic format that will potentially help designers to develop the configuration of buildings to achieve an optimal visual comfort illuminance level of multiple buildings, considering orientation, placement of buildings and building form.

In chapter five, the procedure is applied to two sites, located in Honolulu, Hawaii, and Seattle, Washington, which have two dominant sky conditions: clear and overcast. As a result of these two studies, a variety of building configurations have been created based on the procedure. The outcome of these studies is comparatively analyzed for the effectiveness of the procedure in optimizing the visual comfort illuminance level. Lastly, the optimal configuration of buildings under a clear sky condition is tested under an overcast sky condition and vice versa. The purpose of switching the sky conditions is to observe the differences in illuminance levels and identify possible glare potential mitigation strategies in design development.

The research summary, contribution to the architecture discipline, and the future studies of daylighting in architectural design is discussed in chapter six.

2. DAYLIGHTING IN ARCHITECTURE

Daylight comes from a natural light source and has a dynamic nature of its own. Its nature of constant change brings various perspectives of the world while it maintains human perception of objects.[5] In architectural history, exterior and interior building forms have been designed to create certain dramatic effects within a space. The role of daylighting and its implementation in architecture has significantly evolved over time, from being perceived as an aesthetic design tool to an analysis tool. . In order to understand daylighting effect in architectural design, its metric, design parameters and principles should be clarified through rigorous daylighting analysis.[6] Principles, strategies and tools of daylighting are discussed in this chapter.

2.1. Historical Overview: Light as an Architectural Element

Light is the only media that can reveal the form and experience of architecture. It becomes an element of structure and a material for a building[8] that provides dynamic impression of a space and minds.[9] Consequently, lighting has been recognized as "a fundamental factor in design"[10] which creates the essential element that allows humans to experience architecture. Natural light reveals the exterior form of a building and it creates certain interior spatial qualities.

The history of sunlight can be divided into three periods in western architectural history; the Romanesque period, the Gothic period, and the Baroque period. In the first phase, also called *the Dark age*, architectural construction had been based on heavy masonry walls which generate a protected lighting effect through the great depth of the openings. The effect creates a peaceful, sheltering and retrospective atmosphere.[11] This type of spatial effect with natural light in architecture evoked a feeling of faith which is why it became popular for the design of Romanesque churches. In the later part of the Romanesque period, complexity and spatial layering of daylighting were introduced by the integration of a clerestory (Figure 2.1). In order to maximize the expression of high spirituality, the incident of natural light is utilized to fall into the vaulting and "the 3D elaboration of the nave wall reached their height."[12]

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[5] Karcher, Krautter, Kuntzsch, Light Perspectives, 72.
[6] Anderson, 2008
[8] Kohler and Luckhardt, Lighting in Architecture, 7.
[9] Philips, Lighting in Architectural Design, 3.
[10] Ibid.
[11] Koster, Dynamic Daylight Architecture: Basics, Systems, Projects, 356.
[12] Ibid.

Figure 2.1. Romanesque Church: Saint George-de-Boscherville

In the early Gothic period, sunlight is utilized in creating a contrast between light and shadow with color. The use of masonry walls and a high ceiling configuration still remained as before, but the introduction of stained glass, glazing with colors transformed the interior into "a darkened interior world of color"[18] which escalates the spiritual emotion of the religious space.[19] The daylight through stained glass transforms a space into a transcendental dimension, dissolving harsh shadows (Figure 2.2). At the same time, the amount of light is reduced by the complex patterns of the stained glass windows.

Figure 2.2. Gothic Church: Regensburge Dom

The technique of indirect daylight illumination is introduced in the Baroque period. The actual windows are hidden, so the direction of the light source is unseen. The high vaulted ceiling is lowered in scale and the layers of the open-partitioned walls create ambient spatial quality. As indirect lighting becomes the main theme of the space, direct light is integrated to highlight ceiling paintings, gilded capitals and extravagant figures.[23] In this period, the usage of natural light is expanded in two

[18] Koster, 356.
[19] Ibid.
[23] Koster, 359.

ways (indirect and direct) to create diverse effects in a given space (Figure 2.3). Corresponding to an interior, overall building height is lowered.

Figure 2.3. Baroque Church: Jesuit's Church, The Holy Cross Church of Manapad

In the Modern period, various ways to integrate natural light is explored. The irregularities of openings and exterior geometry allow the daylight to come into a space with dynamic relationships to architectural volumes. The use of colored lenses and surfaces around openings with natural light introduces diffused colored lights to an interior, and various opening sizes, shapes and depth create different degrees of light intensities and the effect of framed light with designed volumes. Light becomes one of the design elements that works with facade and spatial volume designs, at the same time, it is integrated as a method for organizing spaces as shown in the spatial design of St. Ignatius by Steven Holl. The play of volume, color, and the apertures' locations and sizes with natural light all cumulate to create a dynamic spatial quality (Figure 2.4).

Figure 2.4. Ronchamp by Le Corbusier and St. Ignatius by Steven Holl

2.3. Effects of Daylighting

As discussed in the historical overview of daylighting, lighting has evolved as a critical design element in architecture and has been a vital factor in creating a certain environment for humans to form a perception of the space. The dynamic quality of natural light has allowed for light to expand its use in architecture. Consequently, natural light has both psychological and physiological benefits to humans.[26] There are three main elements of light that impact a human's psychological perception. They are ambient light, focal glow, and sparkle. The degree of brightness is determined by the combination of ambient light and focal glow. Sparkle creates a highlight in the environment that "contribute the feelings of well-being."[27] Different proportional uses of these three elements create various emotional effects. Through the brightness contrast in the relationship between surfaces and light, an emotional effect can be created.[28] Appropriate contrast in natural light is important to create an inspiring and supportive spatial quality, and it can be generated by materials and color with lighting.[29] The intensity of lighting also has an impact on the degrees of human stimulation, depending on the types of activities and tasks.[30] Lighting effect can create visual hierarchy and order of a space with the combination of high and low contrast. For a comfortable visual environment, low contrast and an evenly lit environment is ideal because it can minimize the issues of glare and heat gain. The use of natural light can set the evenly-lit environment for visual comfort while contrast and stimulation of lighting can be achieved by the use of electric lighting.[31]

Research shows that "humans have a basic need for windows in buildings"[32] allowing them to make connections to the outside living environment. Daylighting has an impact on the physical and mental well-being of people.[33] Recent research shows that considering daylighting in architectural design has improved classroom performance, productivity in an office environment and patients' recovery state in a hospital.[34] For example, in a 2002 multiple building study by Heschong on skylights and retail sale, the research has concluded that "the skylights account for about a 40% increase in sales"[35] as shown in Figure 2.5. Research at the Lighting Research Center has also discovered that the right quantity and quality of light of daylight trigger the circadian systems which is one of the critical factors in the improvement of people's performance.[36]

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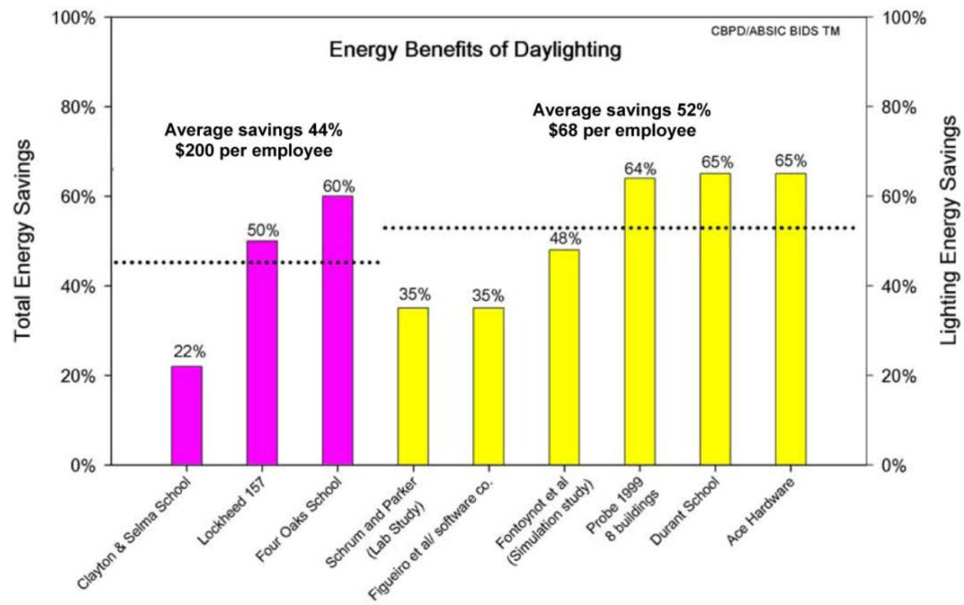
[26] Steelcase, Seeing the Difference, 3.
[27] Ibid.
[28] Birren, Light, Color & Environment, 45
[29] Gordon, Interior Lighting for Designers, 11.
[30] Gordon, 12.
[31] Ibid.
[32] Robbins, Daylighting Design and Analysis, 9.
[33] Ibid.
[34] Leslie, Capturing the daylight dividend in buildings: why and how?, 382
[35] Ibid.
[36] Ibid.

30% to 50% of all the energy consumption in commercial and office buildings is by energy use and heat gain from electric lighting. The efficient integration of daylighting can dramatically reduce the total electricity load and the peak demand[37] so that energy cost can be saved.



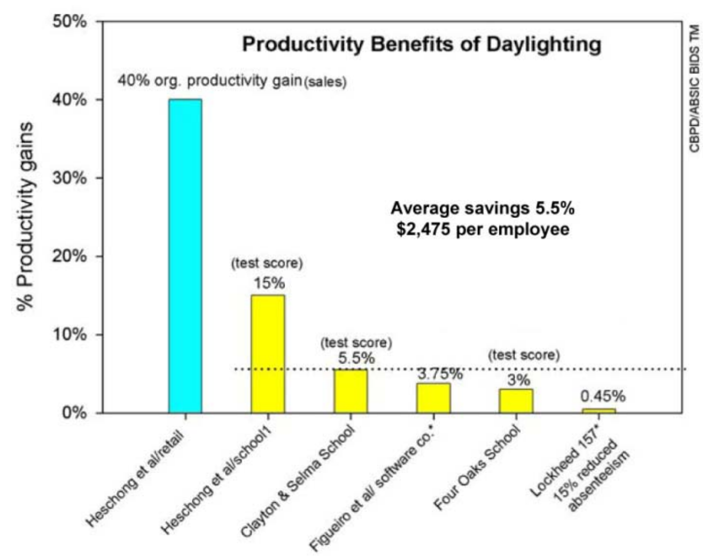


Figure 2.5: NSF/IUCRC Guidelines for High Performance Buildings 2004

[37] Capeluto, 69.

However, daylighting is hard to control because of its dynamic nature of continuous fluctuation due to clouds, weather and time of day. Its properties such as intensity, diffusion, direction and color of daylighting can cause negative effects on people, and they create visually uncomfortable interior. Therefore, the architectural design of building form, apertures and windows is important to avoid glare and excessive heat gain that can result in occupant discomfort.[51] Daylighting design is specifically developed to resolve such issues and enhance the quality of the indoor environment.

2.4. Parameters and Strategies of Daylighting Design

Daylighting is not only hard to control, but it is also a "notoriously difficult building performance strategy to evaluate."[52] Because daylighting impacts various areas of building design and performance, there are different definitions of daylighting based on different professions' interest. Table 2.1shows five different key definitions of daylighting in a building design today.

Architectural definition: the interplay of natural light and building form to provide a visually stimulating, healthful, and productive interior environment
Lighting Energy Savings definition: the replacement of indoor electric illumination needs by daylight, resulting in reduced annual energy consumption for lighting
Building Energy Consumption definition: the use of fenestration systems and responsive electric lighting controls to reduce overall building energy requirements (heating, cooling, lighting)
Load Management definition: dynamic control of fenestration and lighting to manage and control building peak electric demand and load shape
Cost definition: the use of daylighting strategies to minimize operating costs and maximize output, sales, or productivity

Table 2.1. Five Definitions for Daylighting

Basic measurement parameters of daylighting provide fundamental knowledge about what to consider in understanding lighting quality. Complete daylighting parameters and their descriptions are listed in Table 2.2. The most utilized daylighting parameters are illuminance and luminance. They are the metrics that measure the lighting quality between the intensity of light and human perception of a space.

[51] Leslie, 383.
[52] Reinhart and Mardaljevic, Dynamic Daylight Performance Metrics for Sustainable Building Design, 1.

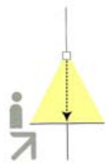
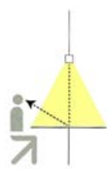
Daylighting Parameters	Description
Radiation (microns)	• The effect when radiation strikes a substance, it is reflected, absorbed or transmitted.
Illuminance (lx = one lumen/m^2 =footcandle) 	• The density of luminous flux (= the time rate of light flow) incident on a surface, area and the size of that area
Luminance (candela(cd)/m^2) 	• The brightness of a surface that emits light • Not just used to measure glare, but considerations such as the adaptation of the eye are not taken into account in this unit of measure. [55] • Not just used to describe reflected light, it can also be used as a dimension for the brightness of luminous surfaces, such as light walls.[56]
Luminous Flux (lm = lumen)	• The time rate of light flow • Light power emitted by a light source
Luminous Intensity (candelas = lumens/steradian)	• The amount of luminous flux in a given direction measured in lumens/solid angle
Reflectance (reflected flux/incident flux) Absorptance (absorbed flux/incident flux)	• When luminous flux strikes an opaque surface
Transmittance (candela(cd)/m^2)	• The product of illumination on the reverse side of a surface and surface transmittance

Table 2.2. Daylighting Parameters and Principles

Once basic definitions and measurement parameters and principles of daylighting are understood, designers can start to make sense of the daylighting quality in a given space and think about the design strategies of a space with natural light. Although there are various sky conditions, natural light is described as two different lighting; sunlighting and daylighting. Lighitng design strategies for sunlighting and daylighting can be summarized in Figure 2.6 and 2.7. The characteristics of sunlighting are fundamentally different than the quality of daylighting even though the term "daylight" includes the meaning of both natural lighting types.

Strategies for dealing with direct sunlight consider the condition of no specific climate, weather, or regional variations that affect lighting quality. The strategies mainly focus on how a building should deal with a beam of direct sunlight by controlling and redirecting it. The goal of the strategies is to use sunlight indirectly and minimize direct sun to avoid glare and heat gain issues that

[55] Karcher and Krautter, Light Perspectives between Culture and Technology, 20.
[56] Ibid.

disrupt visual comfort. As shown in Table 2.3 and Figure 2.6, the effective ways to control direct sunlight are the integration of shade and architecture form.

Sunlighting Strategies	**Description**
Shade	• Prevent glare and excessive heat gain due to direct light • North-south openings illuminate horizontal surfaces well • East-West openings illuminate vertical surfaces well.
Redirect	• Minimize the contrast between the room surfaces and the windows • Integrate ways to spread this directional source, sunlight over a large area to optimize the balance of brightness
Control	• Control the amount of light entering the space • Provide the amount of light required, at the time it is desired • Do not overlight the space (unless directional light is necessary for visually critical tasks or the additional solar radiation for thermal demands
Efficiency	• By shaping the interior and exterior effectively and using high reflectance interior building surfaces, distribute light in a wide area.
Integrate	• Integrate forms for sunlighting with the architecture

Table 2.3. Sunlighting Strategies

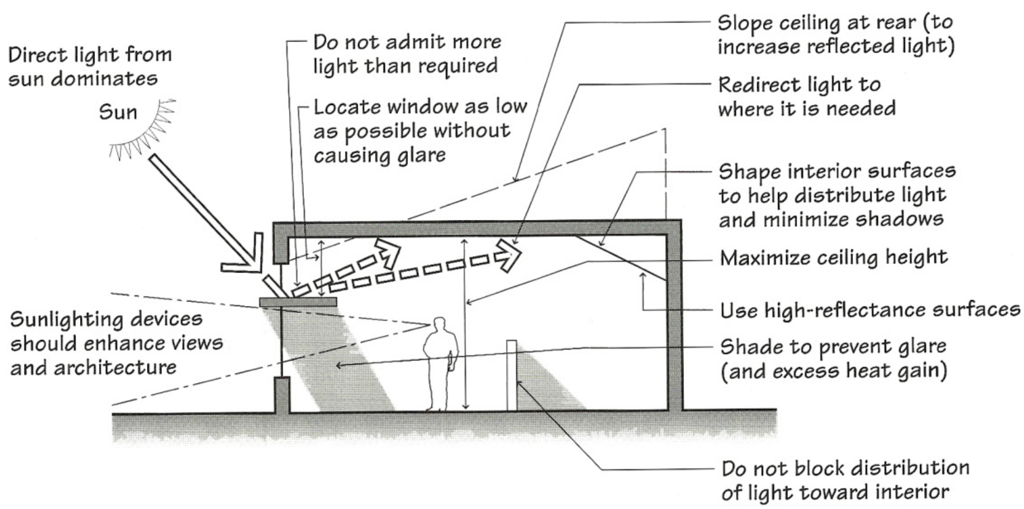


Figure 2.6. Ways to Incorporate Sunlighting Strategies[58]

[58] Egan & Olgyay, Architectural Lighting, 98.

Daylighting Strategies are different from sunlighting strategies in that they are developed for overcast sky conditions, which means there is no visible sun for a substantial percentage of the year.[59] The primary goal of implementing daylighting strategies is to create an ambient environment that provides a comfortable illumination for visual activities and visual delight.[60] In order to maximize adequate ambient lighting quality of a space, daylighting strategies include use of light shelf, aperture placements and appropriate building finish materials as shown in Table 2.4 and Figure 2.7.

Daylighting Strategies	**Description**
Maximize solid angle of sky seen from the task or light-reflecting surfaces.	• Aperture distance from tasks • Appropriate sidelighting aperture size: D <2.5H (see illustration 2)
Shade to prevent glare	• Avoid direct views of the overcast sky • Exterior shading not necessary since it is under overcast sky
Do not block light	• Do not use solid light shelves and overhangs.
Locate openings high	• Openings should see the brightest part of the sky. • High window locations and horizontal skylights provide the best access to light from overcast sky.
Shape space to minimize absorption of light.	• Use high-reflectance interior finishes • Maximize the ceiling height near windows to allow high windows. • Slope ceiling down toward the rear to minimize interior surface area.

Table 2.4. Daylighting Strategies

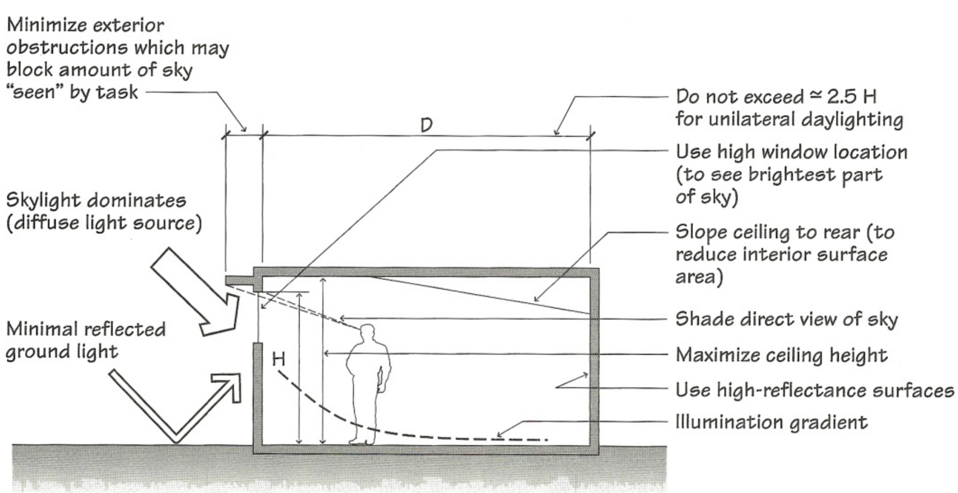


Figure 2.7. Ways to Incorporate Daylighting Strategies

59 Egan and Olgyay, 100.
60 Egan and Olgyay, Architectural Lighting, 98.

2.4. Daylighting Design Metrics and Tools in Architectural Design Process

In the current practice of the architectural design process, daylighting design is mainly perceived as an analytical evaluation preceded in the design development phase. There are both physical and digital analysis tools for evaluating daylighting performance in building design. The aim of these design tools is to visualize the effect of daylighting in building performance regarding issues such as glare and excessive heat gain. The following are some of the critical challenges in integrating daylighting that architecture design faces today.[62]

1. Control of dynamic daylight movement (by hour, season, various climatic conditions)
2. Glare Control: Exterior conditions 10-20 times greater than interior. For example, while indoor office spaces need only about 50 foot-candles, the sun provides 7,000 to 10,000 foot-candles of light.[63] Based on "Daylighting Pattern Guide" by Advanced Buildings, the illuminance level for visual comfort is ranged from 300 lux to 2000 lux.[64] Any area where light level is more than 2000 lux has potential for glare issues.
3. Solar heat gain controls:
    a. Efficacious source of light: 90-120 lumens/watt
    b. Utilize the light while controlling the heat
4. Integration with electric lighting controls: Essential for energy savings
5. User interaction/education: critical for occupants to understand daylight design intent

In order to resolve these challenges by measuring daylighting performance in building design, the following metrics are developed as shown in Table 5.

[62] Rogers, Overview of Daylight Simulation Tools, 6.
[63] Daylighting Collaborative, what/why > what is daylighting?, accessed on December 8, 2011, http://www.daylighting.org/what.php.
[64] Advanced Buildings, Daylighting Pattern Guide, accessed on April, 7, 2012, http://patternguide.advancedbuildings.net/.

Metrics	Description
Daylight Factor (DF = interior /exterior Illuminance)	• Measure under an overcast, unobstructed sky and remains constant regardless of change in absolute sky luminance[68]
Daylight Autonomy (DA)	• Uses work plane illuminance as an indicator of whether there is sufficient daylight in a space so that an occupant can work in daylight alone.[69]
Useful Daylight Illuminance (UDI)	• Dynamic daylight performance measure that is based on work plane illuminances, it aims to determine when daylight level are 'useful' for the occupant (e.g. too dark: <100 lux, too bright: >2000 lux) • This metric has a direct relationship to measure visual and thermal discomfort. • Detect likely appearance of glare
Continuous Daylight Autonomy (DAcon)	• The metric acknowledges that even a partial contribution of daylight to illuminate a space is still beneficial.
Maximum Daylight Autonomy (DAmax)	• Indicate the percentage of the occupied hours when direct sunlight or exceedingly high daylight conditions are present. • Assume glary conditions based on the space type (e.g. computer lab: 150 lux DAmax corresponds to 1500 lux)[70]

Table 2.5. Daylighting Metrics

The most commonly used daylighting metric is Daylight Factor (DF). It ensures an ambient daylighting atmosphere so that an evenly lit environment can be achieved, which is considered to be an ideal spatial condition with minimal glare potential. For example, the LEED (Leadership in Energy and Environmental Design) 2002 Daylighting category utilizes DF as main metric such that once 75% of given space is in the range of DF 2 - 4, the space is considered to be adequately lit. Useful Daylight Illuminance (UDI) is another one of the commonly used metrics, which has set the useful daylight illuminance level (300 lux - 2000 lux) as the daylight performance measure. Illuminance levels more than 2000 lux are considered to have glare potential. The LEED 2009 Daylighting category considers UDI as the deciding factor for visually comfortable space. The DAcon and DAmax metrics are useful when the investigation of daylighting quality needs to be more specific, such as daylighting quality of specific sunlight angles in a day and certain places of a given space. DA is useful when a designer wants to know about the sufficiency of daylight in a space throughout a day or a year.

[68] Moore, Concepts and Practice of Architectural Daylighting, 22.
[69] Reinhart and Mardaljevic, 10.
[70] Rogers, Daylighting Metric Development Using Daylight Autonomy Calculations in the Sensor Placement Optimization, 3.

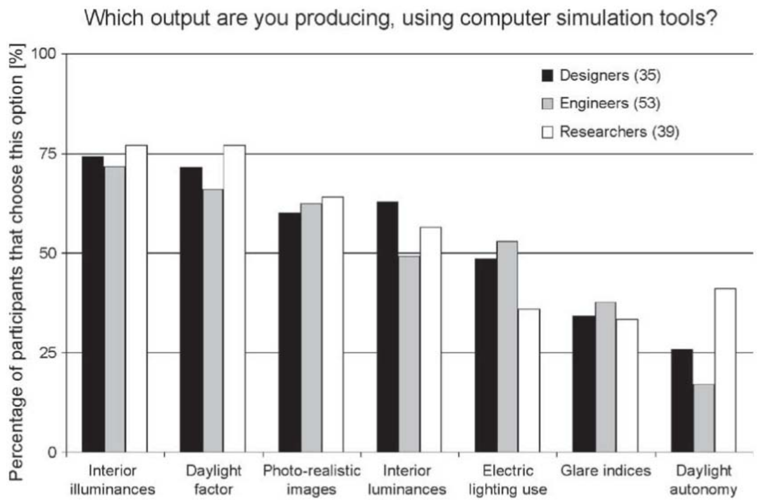


Figure 2.8. Responses given by 35 designers and 53 engineers which outputs they produced using computer simulation programs

As shown in Figure 2.8, interior illuminances and daylight factor are the most utilized metric among designers and engineers in architectural practice today. This is because they inform fundamental daylighting conditions of given spatial surfaces in relation to visual comfort. They also provide a general idea of which area would have glare or excessive heat gain issues. Since visual comfort and resolving glare issues are the most critical concerns to the success of daylighting design,[71] designers seek computer simulation/analysis programs for a daylighting design system that can dynamically visualize interior illuminances and daylight factor.

Both physical and digital tools are viable to visualize those issues, but computer simulation programs perform the analysis process faster and allow users to make modifications easily compared to physical modeling. Computer programs are also "1. less costly to make mistake in a simulation, 2. explore numerous design alternatives cost effectively, 3. explore any geographical location at any time of year, 4. clearly illustrate ideas to client."[72] Based on a report by the VELUX Second Daylight Research Symposium 2007, there are 13 major daylighting simulation tools (both physical and digital) today. In Table 2.6, the capabilities of these currently existing computer simulation/analysis programs are reviewed and their functions are identified across the architectural design process.

[71] An and Mason, Integrating Advanced Daylight Analysis into Building Energy Analysis, 310.
[72] Rogers, Daylighting Metric Development Using Daylight Autonomy Calculations in the Sensor Placement Optimization, 7.

Daylighting Simulation Tools/Methods	Sim. Speed	Schematic Desgin			Design Development						Construction Document	
		Climate Analysis	Solar Shading Analysis	Annual Insolation	Daylight Delivery Systems	Solar Animations	Renderings / Photos	Glare / Luminance Ratios	Interior Illuminance	Glazing Analysis	Electric Lighting Integration	Daylight Responsive Controls
Physical modeling tools												
Heliodon	Slow		F		L	F	S	L	L	L		
Mirror-Box	Slow				L		S	L	L	L		
Outdoor Modeling	Slow		F		S		F	L	S	L		
Computer simulations/analysis tools												
3D Viz	Fast		S			F	F	S	S	L	F	
AGI 32	Fast		S			F	F	S	F	S	F	
DAYSIM	Slow		F	F	S	F	F	F	F	S	F	L
DOE-2	Fast	F		S				S	S	L	L	S
Ecotect	Fast	F	F	F	S	F	F	F	F	F	R	
Lumen Designer	Fast		F			F	F	S	F	S	F	
Radiance	Slow		F	F	F	F	F	F	F	S	F	
SPOT	Slow	S					S	S	S	L	S	S
DesignBuilder	Fast	F	F			F	F	F	F	F	F	F

F: Full ability, S: Some limitations, L: Limited Ability, R: Radiance

Table 2.6. Daylighting Simulation Tools Summary

For physical modeling tools, the Heliodon (simulator for the time of day with lock in latitude and time of year) with a digital video recorder can be utilized to present how the sun patterns work in the interior of physical model. If there is a specific material finish on the interior walls, the model should be made with that material because the light reflectance within the model will affect the quality of interior lighting. The measurement of light reflectance is taken by light meters or a series of light sensors inside of a sky box (mirror box) which is the simulation of an overcast sky for even light distribution. From the series of photos from outdoor modeling, "false-color mapping" images of an interior can be generated to show where the heat gain and glare might become a problematic issue. The use of physical models for daylighting takes a significant amount of time to build and to make any further modifications. The functional capability of the model is limited as well. The accuracy of results from physical daylighting design models might be less accurate than the results from computer models.[73] Therefore, computer analysis/simulation programs are preferred for the purpose of time saving and accuracy, as well as the various capabilities of daylighting design analysis outcomes.

Over 50% of the most widely used daylighting analysis/simulation programs use the Radiance backward ray tracing simulation engine. Radiance is a "highly accurate backward ray tracing engine"[74] and rendering method that simulates light reflection, refractions and shadows.[75] It creates an image of realistic lighting quality in a space by "sending light rays away from the camera rather than into it as actual light does in reality."[76] Radiance "predicts various aspects of daylight illuminance, including the illuminance distribution based on information about the incoming light, the problem of glare, energy savings, and sky luminance distribution."[77] It also has no limitations in expressing material characteristics and modeling so that the visualization of daylighting effect in interior environments is effectual. Examples of Radiance-based interfaces are Designbuilder, Ecotect, DAYSIM, and SPOT.

DAYSIM is one of the Radiance-based programs that has additional detailed simulation functions. It is "a stand-alone daylight calculation software that uses the Daylight Coefficient (DC) method to quickly calculate the diffuse and direct components of daylight in a space over every daylight hour in a year."[78] The DC method is "an efficient approach to compute indoor daylight illuminance through building static fenestration systems."[79] Because it is able to calculate indoor

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[73] Yancey, 5.
[74] Rogers, 16.
[75] "Ray Tracing," accessed on November 28, 2012, http://en.wikipedia.org/wiki/Ray_tracing_%28graphics%29.
[76] Ibid.
[77] Kim & Chung, 211.
[78] An & Mason, 311.
[79] Laouadi & Reinhart, The Daylighting Coefficient Method and Complex Fenestration, 1.

daylight illuminance levels of 65 sun positions on the sun path considering different sky conditions, DAYSIM increases the accuracy of daylighting calculations. The program addresses the shortcomings of other daylighting analysis/simulation tools that only address Daylight Factor (DF). Therefore, DAYSIM expands the capacity of accurate daylighting analysis by using the ever-changing sky conditions and calculating daylight levels from actual sun positions.[80]

Glare control is one of the biggest concerns in daylighting design. The daylighting software, Evaglare, evaluates glare potential. The program analyzes glare problems due to daylight in an office[81] considering the time of a day, time of year and a specific view in a space.[82] It embeds 100 various glare conditions and evaluates the anticipated magnitude of the glare source. The metrics make sure illminance readings of a space are between 300 lux and 2000 lux, which is the visually comfortable illuminance range.

Ecotect is a sustainable design analysis software that is "a comprehensive concept-to-detail sustainable building design tool."[83] The program is capable of operating various daylighting analysis metrics such as shadow and reflection display, calculating daylight factor and illuminance levels of given spaces. The Radiance simulation engine is utilized for visualization of luminance, illuminance false-color rending of a space, and sunlight ray-tracing visualization on certain day and time or all year round.[84] Based on the location setting, the sun path can be set accordingly. The run time of Ecotect's daylighting analysis is faster than other current daylighting analysis programs.

Designbuilder is a sustainable energy and daylighting analysis program that is especially designed to be used in the earliest possible stages of the design process.[85] It can provide a range of climate-based lighting design data including daylight factor data, the interior illuminance level contour plot, illuminance maps and photo-realistic images through advanced Radiance daylight simulation software. It also produces the daylighting credit results of 2002 and 2009 *LEED IEQ Credit 8.1: Daylighting*. Since the program allows manipulation of multiple daylighting metrics all at the same time, it is an efficient and convenient tool for daylighting design in the early architectural design process.

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[80] An & Mason, 312.
[81] Ibid.
[82] An & Mason, 313.
[83] "Ecotect."
[84] "Ecotect: Digital Tools."
[85] "DesignBuilder: BuildingPerfomanceAnalysisSoftware."

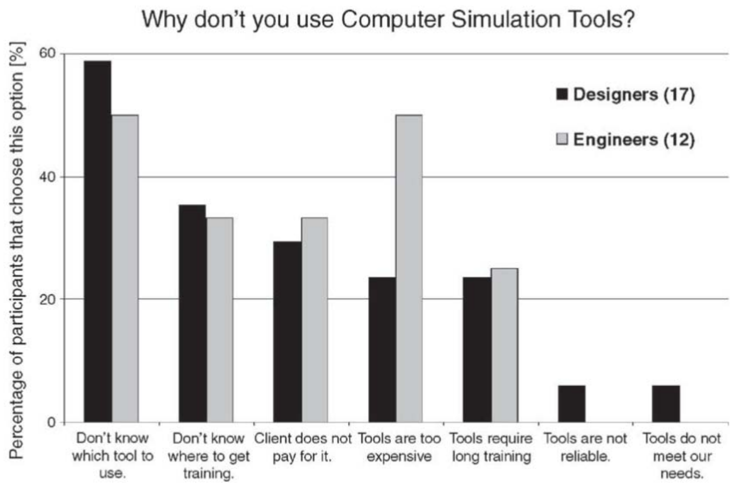

Figure 2.9. Responses given by 17 designers and 12 engineers why they are not using daylight simulation tools

The research survey (Figure 2.9) from Reinhart & Fitz (2006) shows that 29 participants of designers and engineers responded that they do not use computer simulation tools because "primarily they do not know which tools to use."[86] Although design practitioners know the importance and convenience of using daylighting computer analysis/simulation programs, they have not been widely used among designers because of the ambiguities of the tools' use and outcome of the information. There are large numbers of daylighting design computer simulation/analysis programs out there, but there is no program yet that is capable of analyzing and measuring all the necessary daylighting metrics at once. Therefore, the functions are segmented and dispersed in various programs, and designers are often confused about which tools to use and what sequence of proceeding leads to effective daylighting design.[87] Existing daylighting tools are still rudimentary with many limitations for use by designers in early design stages of any architectural project"[88] because the tools are focused on analysis rather than synthesis. Considering the conceptual design stage with natural light, designers need tools that can provide a range of options based on different natural light and sky conditions of site. Current daylighting design tools require exact data, precise details and numbers so that the implementations of these tools in early stage of architectural design is difficult.[89] The survey (Reinhart & Fiz, 2006) on the current use of daylight simulations in building design indicates that current computer tools are reliable and meet their needs if there is a more systematic sequence to use these tools in integrated daylighting design.[90] Consequently, individual tools need to be refined so that there can be viable and clearly understandable tools and systems that operate

[86] Reinhart & Fitz, 830.
[87] An and Mason, Integrating Advanced Daylight Analysis into Building Energy Analysis, 310.
[88] Capeluto, 68.
[89] Ibid.
[90] Reinhart & Fitz, 830.

multiple metrics all at once. Another option can be developing a system that can integrate critical daylighting principles and tools so that designers can follow the procedure to implement daylighting as a synthesis tool.

Most daylighting design tools are evaluation tools, not the generation tools.[91] Evaluation tools "analyze the performance of a given design alternative."[92] In order to use these tools, the alternatives should be designed first because most existing evaluation models is geared to simulate and evaluate finished designs in practice. As architectural design is often performed under a tight schedule and budget, the amount of resources and time to investigate design alternatives are highly limited[93] in the post-design phase. Therefore, performance-driven form synthesis tools or systems are preferred to aid in generating architectural form to achieve visual comfort.

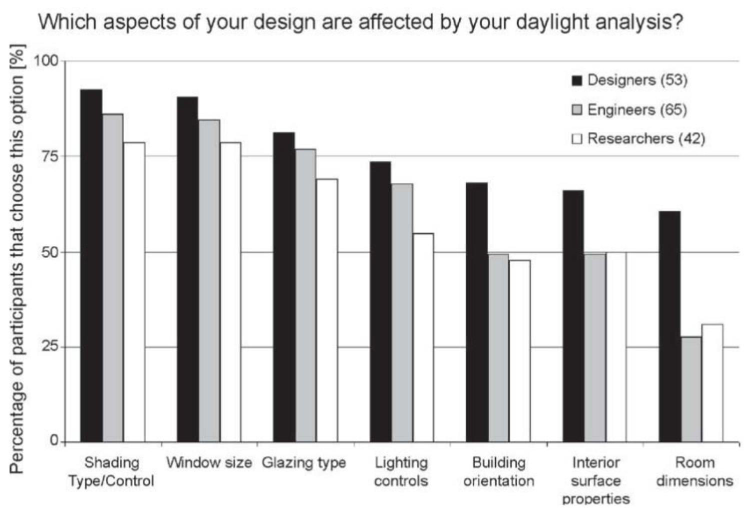

Figure 2.10. Responses given by 53 designers, 65 engineers, and 42 researchers on which building design aspects were usually affected by their daylighting analysis (preference-based)

According to Reinhart & Fitz's survey (2006) in Figure 2.10, designers mainly consider shading type/control, window size and glazing types in their integration of daylighting, which are components decided upon in the design development phase in architectural design. The survey results also show that designers put less emphasis on building orientation. Building orientation is a critical daylighting criteria in the schematic design stage because of the effects that sky brightness and natural light elevation angle have on the fundamental lighting condition of the built environment. Elemental daylighting criteria such as building orientation, form and placement of buildings should be carefully considered in the early design stage.

[91] Capeluto, 69.
[92] Ibid.
[93] Ibid.

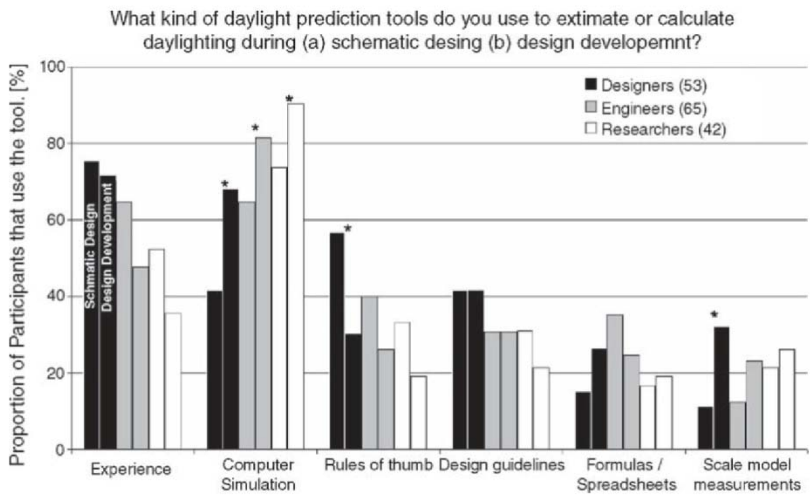

Figure 2.11. Participants' responses ordered by professional group. The two values for each category indicate the responses for schematic design and design development.
(*) mark indicates significant difference

As shown in Figure 2.11, "designers heavily rely on experience from previous work and rules of thumb"[110] in integrating daylighting. Computer simulation programs are mostly utilized during the design development phase than the early design process. In order to explore various possible building configurations for visual comfort, effectual implementation of computer simulation/analysis programs is necessary because the tools allow designers to make design cases with various daylighting settings and metrics. There is also a lack of design guidelines to integrate daylighting throughout the architectural design process, which limits the effective use of daylighting in improving visual comfort. Integrated daylighting design guidelines with selected computer tools should be developed to guide designers to explore various design options for satisfactory visual comfort.

[110] Reinhart & Fitz, 829.

Architectural Design Phases		Current Daylighting Integration: Function	Current Daylighting Integration: Tools
Schematic Design	deciding on overall concept + basic building location/volume design	Part of site analysis: Identifying the surrounding condition of given site	Sun dials or Ecotect: Stereographic projection of a sun-path diagram of the site
Design Development	focus on details of project	deciding on locations of openings, window properties	Heliodon or Radiance-engined simulation software: illuminance map, false-color renderings
Construction Document	communicating the design	integration of electric lighting	Radiance-engined simulation software

Figure 2.12. Current daylighting design in architectural design process

Daylighting has been integrated throughout current architectural design process. As shown in Figure 2.12, daylighting simulation/analysis is mostly emphasized during design development phase because daylighting is integrated to decide on locations of openings and window properties after the building design is almost finalized.[111] In the early design stage, integration of daylighting is a part of site analysis focused on surrounding buildings and trees of the given site. Shadow range analysis can inform how buildings shade each other and how target building is affected by other buildings' shadow as shown in Figure 2.13. In order to understand the shadow pattern thoroughly, site's shadow range is illustrated from 9AM to 3PM in winter solstice, equinox and summer solstice.

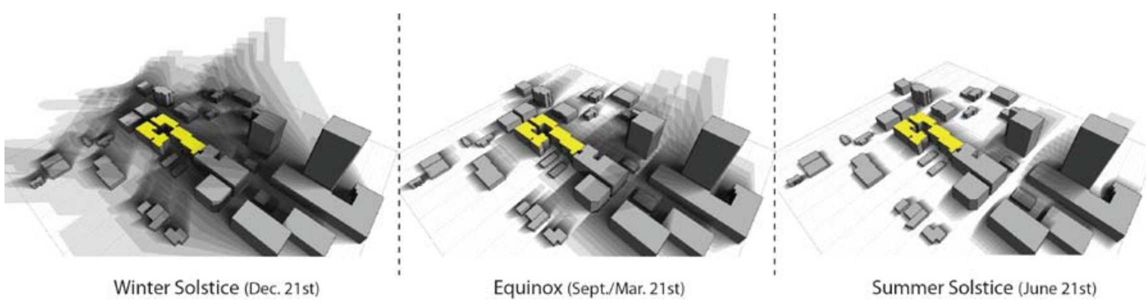

Figure 2.13. Site shadow range analysis: 9AM - 3PM (location: Seattle, WA, latitude: 47.5 deg. N)

The stereographic projection of site shading is also performed during the schematic design phase. The projection informs the hour range when target building is shaded on the projection of

[111] Yancy, The Daylighting Design Process, 13.

sunpath and shading mask on 2D sphere layout.[112] This illustrates the shadow of tall buildings around the target building that would significantly affect daylighting access to the building. As shown in Figure 2.14, the hours of sunlight access for target building's each side can be understood through shading projection. This part of daylighting analysis is proceeded as a part of the site analysis.

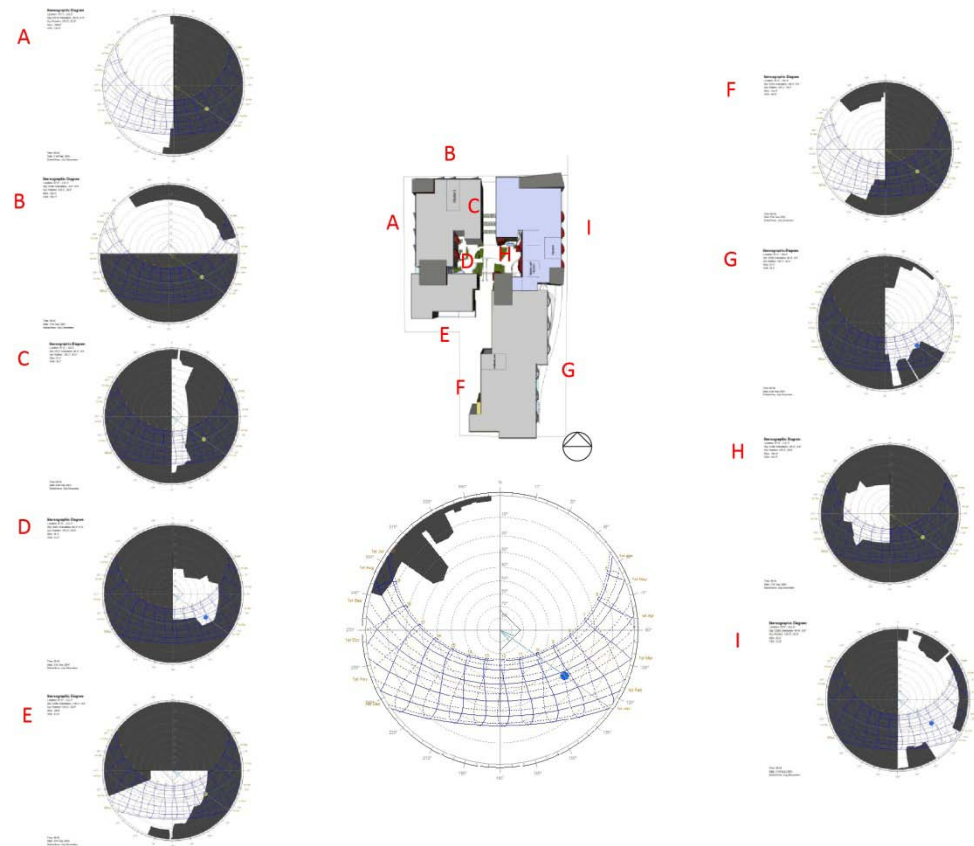

Figure 2.14. Stereographic projection of site shading

Once building design is developed, daylighting analysis of building facade is performed during the design development phase. The purpose of the analysis is to determine the location and size of openings, proper window properties considering the orientation of building sides, interior surface material, and shading options. Most analysis regarding daylighting is done in this phase. As shown in Figure 2.15, four main daylighting performance simulations of building interior can be generated by Radiance-engine software such as Ecotect. Hight Dynamic Range (HDR) image shows the perception of an interior as if a human is looking into the space. Luminance Contour Map identifies the brightness of floor or wall surfaces that emits light.[113] Its contour lines describe a

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[112] Sky Illuminance, Ecotect Community Wiki, accessd on February 5, 2013, http://wiki.naturalfrequency.com/wiki/Sky_Illuminance.
[113] Karcher and Krautter, Light Perspectives between Culture and Technology, 20.

dimension for brightness, and the map is useful to measure glare. False Color Rendering is another form of luminance map that shows surface brightness and glare potential with the color legend of luminance scale.[114] Red color represents intense brightness of the surface which means there is glare potential. Visually comfortable surface brightness is the luminance range of 20 to 2000 cd/m2. Illuminance map is mostly used for measuring the density of luminous light on a surface which represents the light level on a surface. For example, LEED 2009 Daylighting credit requires that at least 75% of all the regularly occupied spaces achieve daylight illuminance level of [300 lux, 5000 lux].[115] Under two representative sky conditions; overcast sky and clear sky, these daylighting analysis are simulated to study lighting quality of building interior spaces.

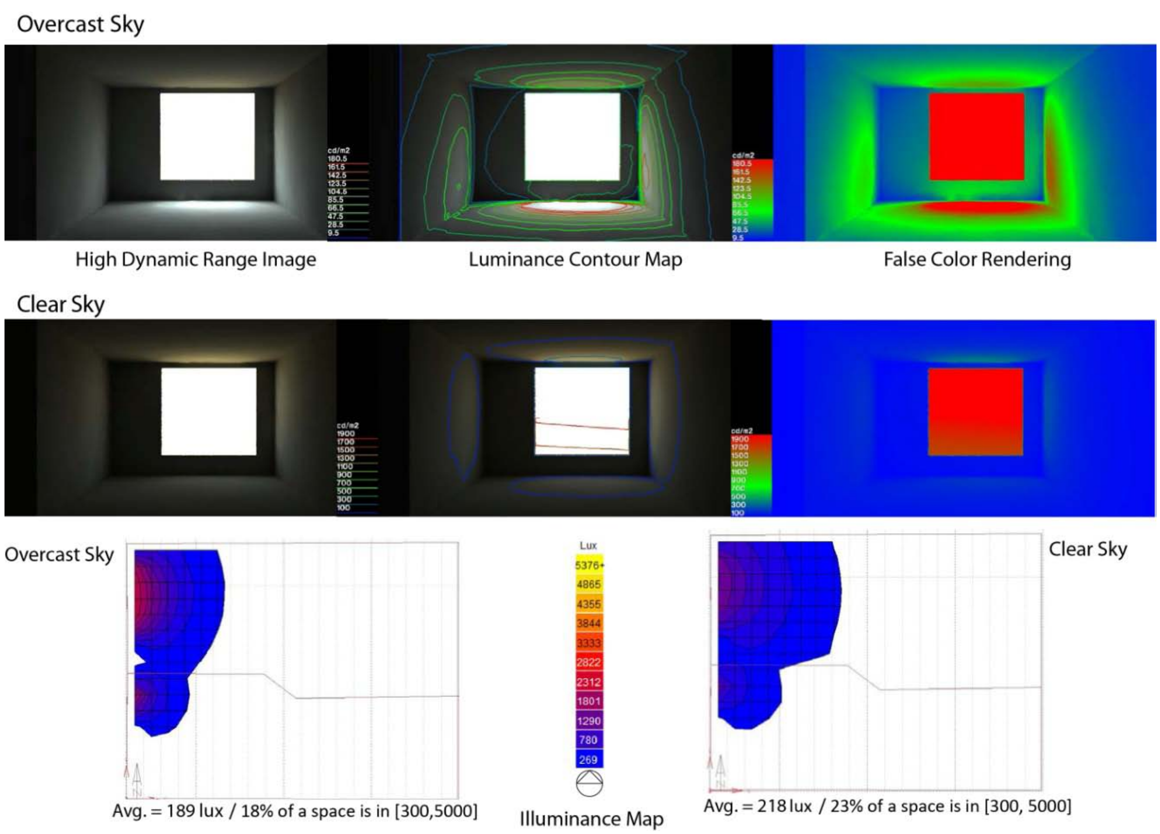

Figure 2.15. Four mostly used daylighting simulations: Equinox @ 9AM in Seattle, WA

Daylighting simulations are repeated with various opening designs of a building as shown in Figure 2.16. Keeping the same wall to opening ratio, different placements and shapes of windows are examined in the design development phase. In this phase, daylighting analysis aids architecture design

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[114] Advanced Buildings, Daylighting Pattern Guide, accessed on April, 7, 2012, http://patternguide.advancedbuildings.net/.

[115] U.S. Green Building Council, 2009. LEED Reference Guides for Green Building Design & Construction, 77.

to finalize the details of building facade that assures adequate lighting access. However, the analysis is conducted after the building form is determined, so the opportunity for daylighting to impact the architectural design is limited.

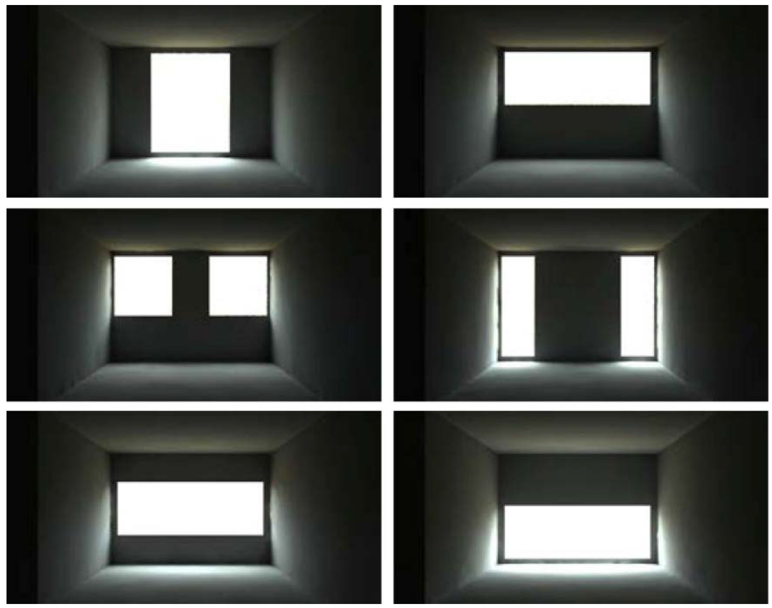

Figure 2.16. Various aperture designs with the same opening to wall ratio:
HDR image under Overcast Sky @ 9AM in Seattle, WA

2.5. Summary

The historical overview of daylighting informs how daylighting has been implemented to create certain interior spatial effects. Throughout the history, daylighting has been perceived as a design element that can enhance the quality of the interior and create an art of a space. Many research shows that daylighting also provides both psychological and physiological benefits. People feel better and become more productive when there is an effective daylighting integration in the built environment. The goal of daylighting integration lies in aiding spatial design for creating a visually comfortable environment.

In the growing need of environmental sustainability, visual comfort is an important environmental criteria in building performance. There are various physical and computer simulation/analysis tools to measure the condition of visual comfort for design practitioners. However, there are no clear directions or guides about which tools to use and how these different tools can be integrated to successfully strategize daylighting design in the architectural design process. In current architectural design process, the consideration of daylighting criteria has more weight on the post-design phase compared to the early design stage because current daylighting tools and systems are strictly analysis-based. This limits the opportunity to examine the quality of daylighting in relation to other buildings and visual comfort in a larger context. These is a need for a daylighting design guide that can provide steps to achieve satisfactory visual comfort in buildings in the perspective of daylighting synthesis at the early architectural design stage. The following chapter presents exemplary cases of how the daylighting design can be implemented as a synthesis tool in designing buildings and urban-scape form.

3. DAYLIGHTING IN FORM CHANGES

As seen in an historical review of natural light, daylighting influences architectural design significantly. The following two studies present how daylighting can be a critical design factor in a building design. The first study discusses how daylighting design impacts the roof form and skylight design of a museum. The main issue of the existing museum has been heat gain on artifacts. The study presents a methodology how the issues have been addressed. The second study is about utilizing daylighting as a synthetic tool to design urban-scape. This study has made an effort to find the daylighting design pattern and atrium building block prototype to achieve standard visual comfort level in multiple units of the building. While the daylighting study is integrated to modify a part of a single building form in museum's roof and skylight redesign project, the study of the atrium building form explores the possibilities of designing urban block with daylighting as a synthesis tool in the early design stage. These two studies demonstrate how daylighting design can be integrated as a synthesis tool to makes a significant design impact on both single and multiple buildings in small and large scale.

3.1. Daylighting in Modifying the Architectural Form

This first study uses assorted computer analysis/simulation tools to redesign a roof of the Seoul Museum of Art (SMOA) with a goal of resolving heat gain issues. In this process, a methodology called, Daylighting Simulation Integrated into the Architectural Design Process (DSADP) is applied. The main computer analysis/simulation program used in this process is Radiance, so that the lighting environment can be accurately represented under clear sky conditions.[142] SMOA has been initially designed with daylighting to have “the natural illumination of surfaces that adds a quiet sparkle to spaces.[143] However, irregular distribution of daylight and excessive sunlight from current skylights has started to damage artworks.

As daylighting design solutions, a monitor-shaped toplight system (MTS) and a sawtooth-shaped toplight system (STS) were considered initially. The experiments of the skylight shapes were mainly conducted through Radiance. The flow chart (Figure 3.1) shows how the daylighting analysis has been implemented in this study to resolve specified daylighting issues and the modification of architectural form.

[142] Kim & Chung, Daylighting simulation as an architectural design process, 210.
[143] Ibid.

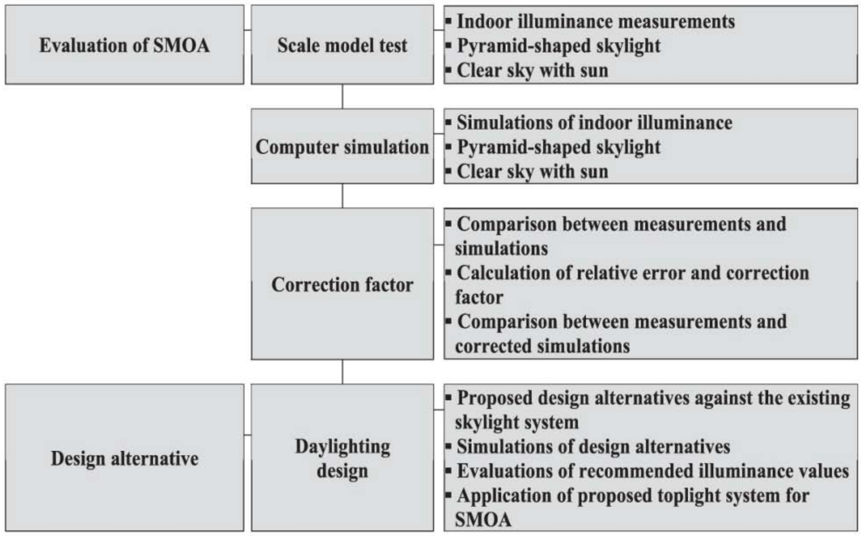

Figure 3.1. DSADP Flow chart: steps of research process

The evaluation of the museum design has gone through both the physical model and the computer simulation tests in order to get the most accurate information about the current issues. The simulations were carried out at noon on the summer solstice, autumnal equinox, and winter solstice. Simulation models were a Pyramid-shaped Skylight (PSS), a Monitor-shaped Toplight System (MTS) and a Sawtooth-shaped Toplight System (STS). PSS model's dimensions and height of aperture size has been modified first. Then, MTS and STS models have gone through glare and illuminance analysis of the space (Figure 3.2).

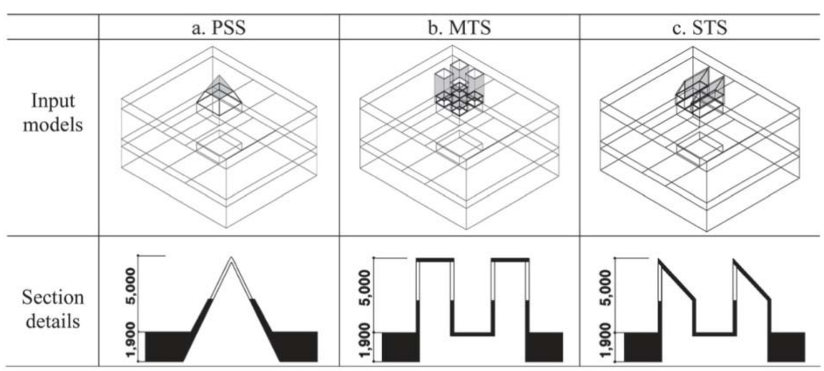

Figure 3.2. Simulation models for RADIANCE

Based on the recommended interior illuminance value for SMOA (by utilizing Radiance), the expected light transmittance values were determined. Considering effective transmission values for various glazing shapes, the following skylight shapes were tested with two different skylight depths;

1.5 m and 3.0 m (Figure 3.3). The transmission value for the flat skylight shape has been the highest, which has high potential to create glare issues. MTS has the lowest light transmission value which is identified as the ideal shape for glare-free skylight for the museum.

Shape	Base Case	Flat	Pyramid	Dome	Barrel vault	Ridge	Sawtooth	Monitor
	No canopy							
Well depth l 1.5 m	100	70.89	68.99	66.70	69.01	69.07	1.80	1.78
Well depth 3.0 m		71.95	70.13	68.07	70.42	69.91	1.37	1.37

Figure 3.3. Effective transmission values for different skylight shapes

Then, PSS, MTS and STS model simulation tests have been conducted under clear sky condition in summer solstice, equinox, and winter solstice. For each model, 5 different variations were created in terms of various opening sizes and photo-realistic renderings of interior daylight effects (Figure 3.4). From the variations, the goal has been to find the toplight system that would reduce the light transmittance efficiency from 90% to 40%.[151]

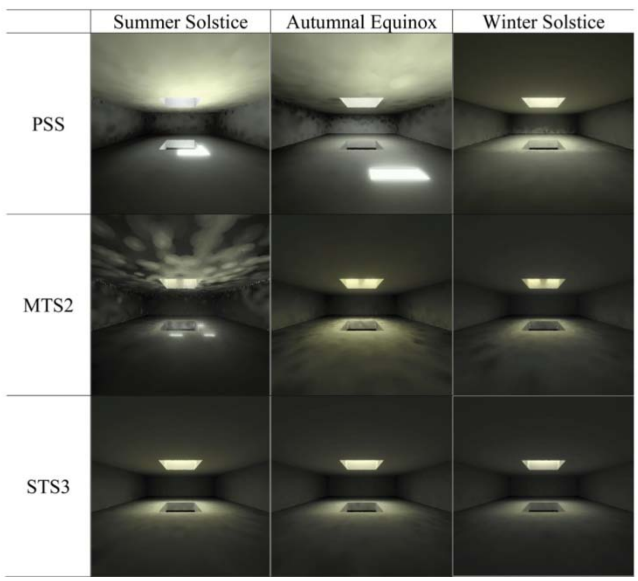

Figure 3.4. Luminance photo-realistic renderings: PSS, MTS and STS models

STS3 model has demonstrated the most reduction of light transmittance efficiency and ensured the most stable illuminance distributions. When simulations have been carried out to find which skylight shapes block direct sunlight the most effectively, STS3 has been also the most effective in blocking direct sunlight. Combining the appropriate light intensity (lux) of the glazing, the 60STS3, 70STS3, and 80STS3 were chosen as the alternative shapes for SMOA's skylight to resolve the issues of glare.

[151] Kim & Chung, Daylighting simulation as an architectural design process, 219.

This study shows that systematic implementation of daylighting design sequence such as DSADP can modify a part of the building form for a visually comfortable environment. If daylighting is considered in the early design stage, the shape of skylight and roof form could have been designed appropriately. DSADP utilizes Radiance as computer simulation/analysis tool in this study to "accurately represent the lighting environment within an indoor exhibition space under clear sky conditions"[152] to find effective alternative design for skylight shape of a single building. In order to determine effective building form that creates visual comfort, an integrated system with essential daylighting design principles and tools should be developed in the relationship of multiple buildings.

3.2. Daylighting Implementation in Creating Urban Form

The study explores development patterns that support better daylighting from a single atrium building form to multiple building forms in an urban block. Specific use of daylighting design tools has not been identified in this study, but the story of developing urban pattern from sizing and configuring a single atria building demonstrates the possibility of designing urban-scape that can ensure visual comfort with multiple buildings. The rationale of the study is that the use of daylighting is the single most cost-effective way to reduce energy use in buildings in the growing industry of sustainable design, and the natural light simply allows human to have the most fundamental presence of nature in the relationship with sky and surroundings.[155]

The atrium building form is a good beginning strategy of developing urban development patterns with daylighting because its architectural form itself has a lot of flexibility to rearrange the outer surrounding building volumes in various ways.[156] The methodology of the study is finding the appropriate proportion of the size of the atrium and building thickness with given building height and location latitude based on target daylight availability as shown in Table 3.1.

[152] Kim & Chung, Daylighting simulation as an architectural design process, 222.
[155] Dekay, Dayligthing and Urban Form, 36.
[156] Ibid.

Latitude	Required DF
28°-38°	1.5-2.0
40°-48°	2.5-3.0
50°-52°	3.5-4.0
54°	4.5

°Latitude	DF required IES C 10-20 fc	IES D 20-50 fc	Atria H/L* Ratio	Length (L)** 4-story	6-story	10-story
28	1.0-1.5	1.5-4.0	1.60			
30	1.0-1.5	1.5-4.0				
32	1.0-1.5	1.5-4.5	1.60	30 ft.	45 ft.	75 ft.
34	1.0-2.0	2.0-4.5				
36	1.0-2.0	2.0-5.0				
38	1.0-2.0	2.0-5.5	1.35	*36 ft.*	*53 ft.*	*89 ft.*
40	1.0-2.5	2.5-5.5	1.20	40 ft.	60 ft.	100 ft.
42	1.0-2.5	2.5-6.0				
44	1.5-2.5	2.5-7.0				
46	1.5-3.0	3.0-7.5				
48	1.5-3.0	3.0-8.0	1.10	*44 ft.*	*65 ft.*	*109 ft.*
50	2.0-3.5	3.5-9.0	0.95	51 ft.	76 ft.	126 ft.
52	2.0-4.0	4.0-10.0	0.85	*56 ft.*	*85 ft.*	*141 ft.*
54	2.0-4.5	4.5-11.5	0.75	*64 ft.*	*96 ft.*	*160 ft.*
56	3.0-5.5	5.5-14.5	0.65			
58	4.0-8.0	8.0-20.0	0.40			
60	5.5-11.5	11.5-28.5	N/A			

Table 3.1. Required average daylight factors by latitude (top), DF and atria proportion required under overcast sky (bottom) with floor-to-floor height = 12' per story

The results concerning atrium building form is: as location latitude decreases, the building's gross floor area to net rentable floor area ratio (FAR) increases with building height. As the location latitude increases, atrium area as building footprint should be increased to ensure adequate daylight access. As building height increases, atrium area also needs to grow larger. Generally, larger atria is needed for higher latitude, and the taller the building the larger atrium is needed for the lower level of the building to have required daylight access.

The size of an atrium can be translated as distance among buildings, so based on the atria building module formula (Atria Building Module = Atrium length + Building thickness), set dimension of atrium blocks can be found, considering the given building height and required FAR. Figure 15 is the example of minimum atrium block sizes for 40 - 48 degrees latitude, assuming a 20 footcandle (215 lux) minimum illumination level during 85% of working hours annually.

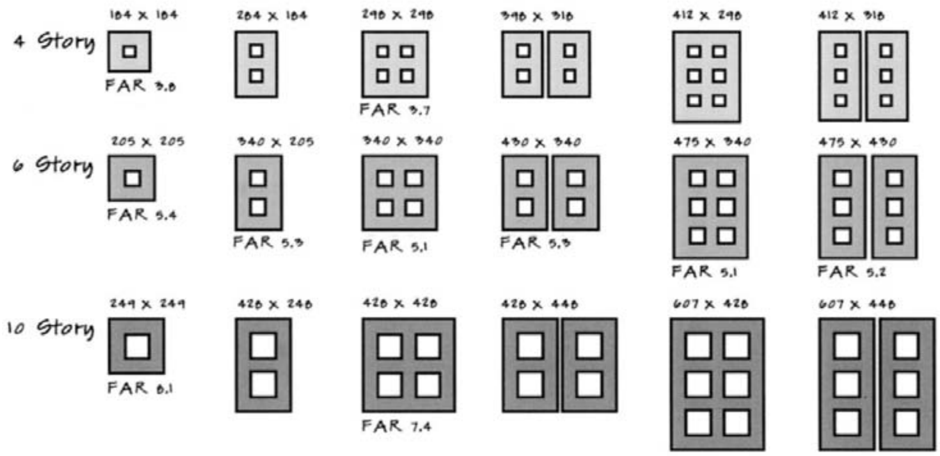

Figure 3.5. Example of Atrium blocks: minimum block sizes for 40 - 48 degrees latitude

The method of atrium block sequences creates a footprint of urban pattern. In order to generate daylit urban sequences in 3D building form, certain 3D volumetric form with height constraints should be determined as shown in Figure 3.5. Consequently, the study introduces the concept of *Climatic Envelope* which is the composite of *Solar Envelope* and *Daylight Envelope*. While *Solar Envelope* ensures the access of direct solar light to the site (Sarkar, 2009), *Daylight Envelope* assures adequate daylight access, ambient light to the street and adjacent buildings by shaping and spacing buildings.[157] *Climatic Envelope* (DeKay, 2010) integrates a full spectrum of natural light, limiting urban block volume growth that both solar and daylight access are insured (Figure 3.6). The possibility of integrating daylighting as synthetic tool is realized through DeKay (2010)'s introduction of *Climatic Envelope*. If daylighting can be perceived in the urban-scape, it can impact the design of buildings in the relation to each other. This can be the starting point of constructing urban form where visual comfort is ensured. The concept and construction of *Climatic Envelope* will be further discussed in Chapter 4: Daylighting as a Synthesis Tool.

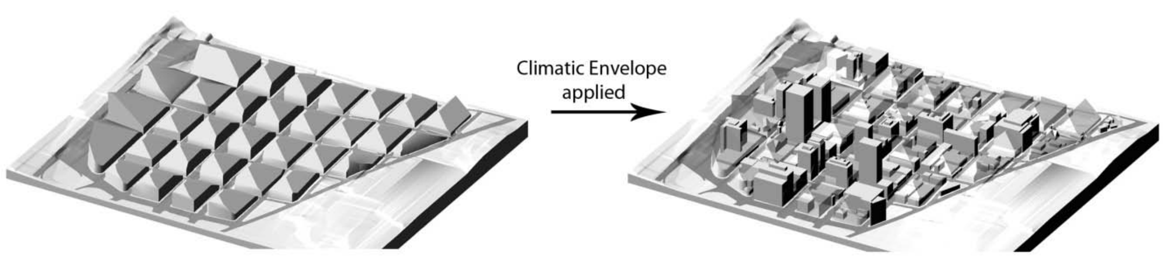

Figure 3.6. Example: Climatic Envelope applied in Downtown Chattanooga, TN

[157] Brown & DeKay, Sun, Wind, & Light, 110.

3.3. Proposed Daylighting Integration in Architectural Design Process

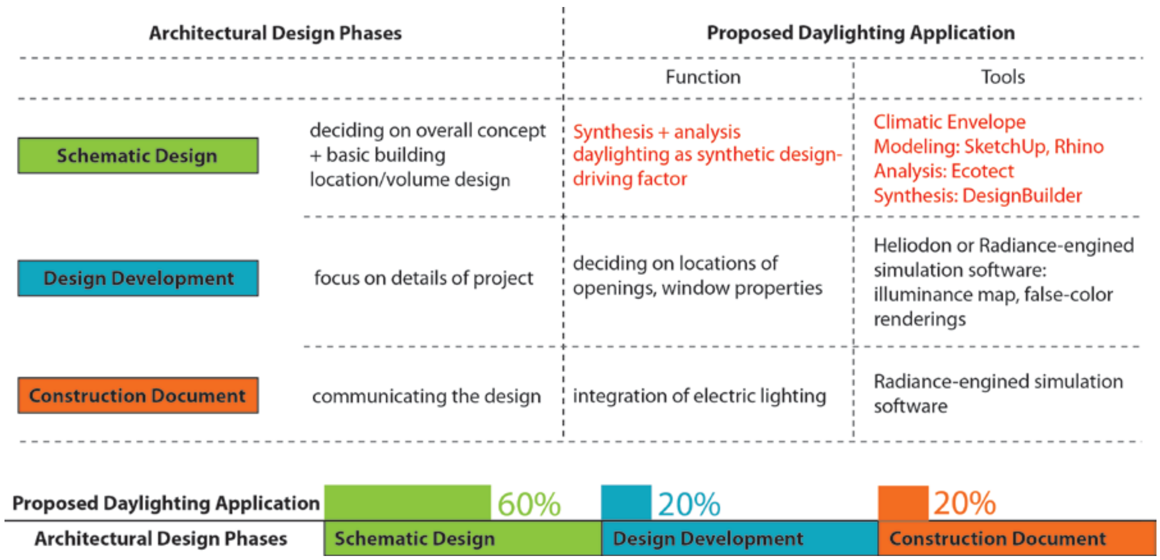

Figure 3.7. Proposed daylighting integration in architectural design process

The concept of *Climatic Envelope* opens the opportunity to integrate daylighting as a synthesis tool so that daylighting becomes a key design factor to generate 3D volumetric boundary, which ensures the access of both sunlight and ambient light. Daylighting can be implemented as synthetic design-driving factor in the early design stage and informs initial design of buildings considering their relationship with daylighting at the given site (Figure 3.7). The way daylighting is integrated in design development and construction document phase stays the same. The configuration of buildings, which is generated in schematic design, will set the relationship of multiple buildings with optimal visual comfort. By emphasizing the integration of environmental factor such as daylighting in the early design stage, architectural design can be started with environmentally conscious design setting. Daylighting design framework and the procedure in the next chapter will guide architects to integrate daylighting as a synthesis tool to generate configuration of buildings with satisfactory visual comfort.

3.3. Summary

While Daylighting Simulation integrated into the Architectural Design Process (DSADP)' framework has shown the case that daylighting drove architectural form modification, the study of atrium building form and the concept of *Climatic Envelope* is the beginning of integrating daylighting as a synthetic design factor that affects the visual comfort performance of buildings. These two studies have provided micro- and macro- scale of implementing daylighting in architectural design. Daylighting can have significant impacts on a single architectural building design and its visual comfort performance. However, daylighting design can influence urban form as well the macro scale of architectural design. This is because daylighting touches on various aspects of human lives from the built environment to the urban environment. This research will further explore the design synthetic possibility of daylighting design in urban-scape.

4. DAYLIGHTING AS A SYNTEHSIS TOOL

This doctorate research attempts to create a comprehensive integrative daylighting system in the configuration of buildings by combining the aspects of synthetic daylighting principles in an urban-scape. The building models are initially created from the synthesis of *Climatic Envelope*, 3D boundaries which open up the opportunity to increase the visual comfort level in multiple buildings in a given site. The design rules are then applied to guide designers to configure buildings under appropriate dominant sky conditions, according to given site conditions. The design sequence between *Climatic Envelope* and design rules for configurations of buildings is proceeded to find the optimal urban block design for satisfying the visual comfort illuminance level. Generated urban-scape design informs orientation, placements, the relationship between building heights and width and forms of multiple buildings for achieving adequate average visual comfort.

4.1. Daylighting Synthesis Framework

This proposed framework requires four procedures as shown in Figure 4.1: 1) the application of *Climate Envelope*, 2) the decision on dominant sky condition, 3) the application of the design rules for the configurations of alternatives, and 4) the design iteration if average visual comfort is not satisfied.

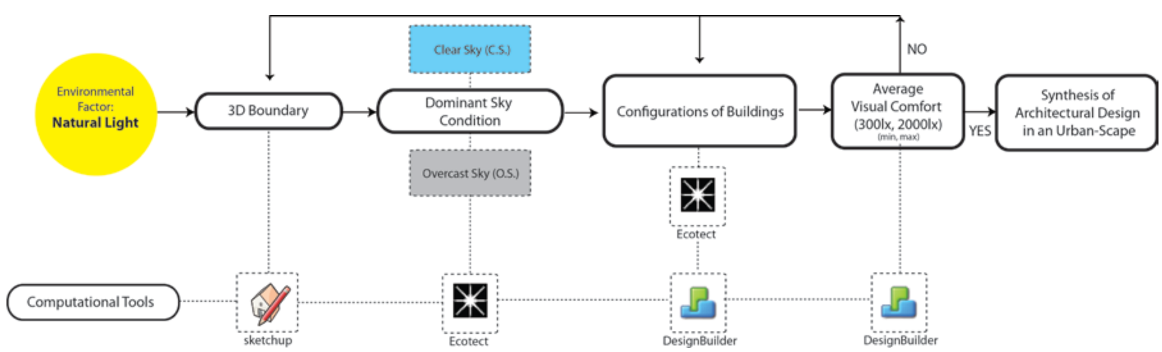

Figure 4.1. Framework: Daylighting synthesis of multiple building in an urban-scape

Considering latitude, dimension and orientation of the given site, *Climatic Envelope* is constructed over the target site lot. The envelope provides a 3D volumetric boundary of urban block design, so it can confine growth of buildings in height, size and volume. When the envelope is constructed, a part of existing buildings are cut off by the envelope's 3D boundary condition in SketchUp. Dominant sky conditions; clear and overcast sky conditions of the given site are determined according to the geographical location of the site with the help of Ecotect. Based on the sky condition, the designer chooses the appropriate design rules for synthesizing the configurations of buildings. The cut building volumes from the result of *Climatic Envelope* and buildings themselves are reconfigured based on the orientation of the site, the placement of the buildings and the buildings' forms in design rules. Reconfigured variations are transferred to DesignBuilder for verification of visual comfort levels. Through the procedures, Ecotect is employed for reviewing shadow patterns to understand the relationship among buildings' height and their distances relating to the illuminance results of target buildings. If the visual comfort level of the configuration does not reach closer to the average visual comfort standard, the application of *Climatic Envelope* and the design rules of the reconfigurations of alternatives are repeated.

4.2. Setting up 3D Volumetric Boundary Condition

Solar envelope and Daylight envelope are two representative theories regarding natural light in designing a building form. They are the product of latitude, built context, size, shape, and orientation of the site. While *Solar Envelope* ensures the access of direct solar light to the site,[172] *Daylight Envelope* assures adequate daylight access, ambient light to the street and adjacent buildings by shaping and spacing buildings.[173] *Climatic Envelope* (DeKay, 2010), the composite of solar and daylight envelope, deals with both direct sunlight and daylight in order to integrate a full spectrum of natural light under both clear and overcast sky conditions. As shown in Figure 4.2, *Climatic Envelope* is employed as a 3D volumetric boundary to constrict the growth of height and width of the given site which limits building's volume growth to satisfy average visual comfort of the buildings.

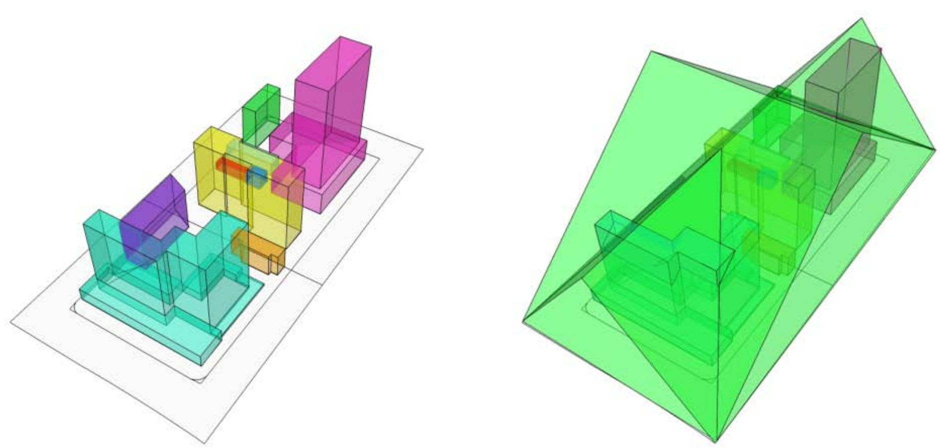

Figure 4.2. Climatic Envelope: Honolulu, HI (Latitude: 21.3 degrees North)

[172] Sarkar, 2009.
[173] Brown & DeKay, Sun, Wind, & Light, 110.

Since *Climatic Envelope* is the composite of solar and daylight envelope, they have to be constructed first. Brown & DeKay (2001) descriptively summarized construction of solar and daylight envelope in their book, "Sun, Wind & Light." Once solar envelope and daylight envelope are constructed over the given urban block, *Climatic Envelope* takes the part where two envelopes overlap. There is no specific order of constructing which envelope first. The following illustration demonstrates how the *Climatic Envelope* can be constructed.

1. Construction of *Solar Envelope*

Solar Envelope is developed by Knowles (1981). It is defined as the maximum buildable volume in a given site that adjacent sites are not shaded and solar access is guaranteed for all buildings.[174] Site size, orientation, latitude, and desired time for solar access are determinant factors for the size and shape of the Solar Envelope.[175]

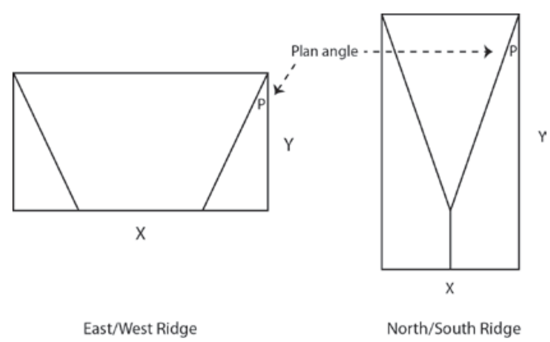

Figure 4.3. 2D Illustration of Ridge Heights of Solar Envelope (where X and Y are site dimensions) (Brown & DeKay, 2001, pp.92)

Seattle, WA is selected for the *Solar Envelope* construction demonstration. First, the appropriate ridge height is determined according to the ridge factor of different latitudes as shown in Figure 4.3. Different ridge factors are identified in "Sun, Wind & Light" (2001). This sets up the maximum height of buildings for the given site. Based on Brown & DeKay (2001)'s ridge factors table, plan angle P and Seattle's appropriate ridge height of the envelope is determined. Since Seattle's latitude (47.5 degrees North) is close to 48 degrees North, plan angle is 49 degrees with EW ridge height: 0.18y and NS ridge height: 0.09x. When the latitude of the site is 40 degrees North and beyond, the sun does not get to the north of the east or the west side which means it never casts a shadow to south between 9 AM and 3 PM. Therefore, the south face of the *Solar Envelope* is vertical from the edge of the site where its latitude is 40 degrees North and beyond.[176] The envelope of the

[174] Brown & DeKay, 89.
[175] Ibid.
[176] Ibid.

site in Seattle is created step by step in the NS (North-South) direction as shown in Figure 4.4. Concerning direct sunlight access, the NS direction is the most appropriate for the *Solar Envelope* because it lets the site be exposed to sunpath movement which moves from the east to the west. By constructing this envelope, sunlight access is ensured for the given site.

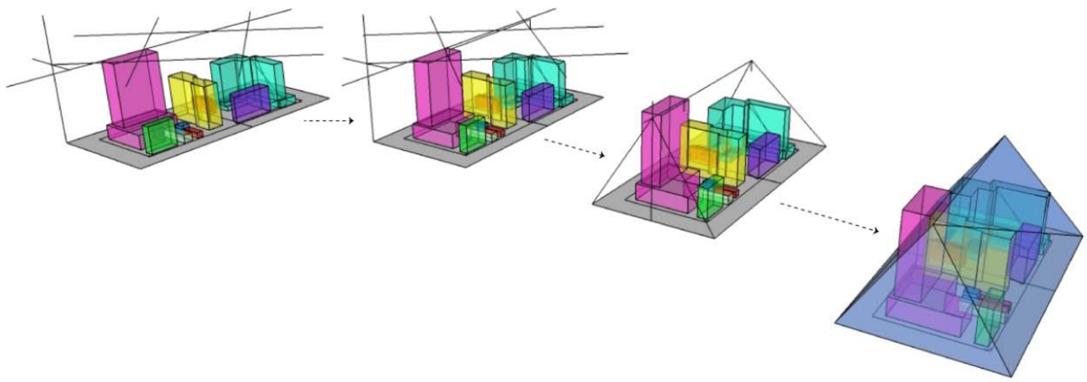

Figure 4.4. 3D Illustration of constructing Solar Envelope for Seattle (latitude: 47.5 degrees North)

2. Construction of *Daylight Envelope*

The concept of *Daylight Envelope* is developed by Brown & DeKay (2001). This envelope assures adequate daylight access to the street and adjacent buildings by shaping and spacing buildings in a given site.[177] The term, daylight has a different meaning than sunlight. The source of both lighting terms is from natural sun, but daylight refers to ambient and diffused light under an overcast sky condition while sunlight refers to direct light under clear sky condition. Therefore, envelope types corresponds to lighting types. While *Daylight Envelope* protects access to light that comes from the entire sky dome, *Solar Envelope* ensures direct-beam sunlight based on sun angles of a given location.[178] A *Daylight Envelope* offers "a prescriptive development control " and defines the maximum volume of the given site to protect daylight access to neighboring buildings.[179] In order to maximize access of light to buildings, street wall height and spacing angles between buildings should be determined, as shown in Figure 4.5.

[177] Brown & DeKay, 110.
[178] Ibid.
[179] Ibid.

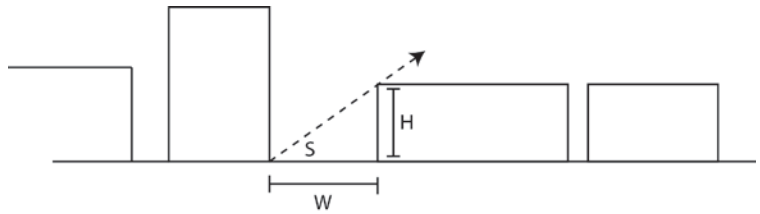

Figure 4.5. The Relationship between building height and spacing angle S in Daylight Envelopes

Daylight Envelope is constructed in the EW direction of the site according to DeKay (2013) because it concerns with diffused light from entire sky, not directional light. Therefore, sunpath is not a concern for the daylighting. Based on the "Daylight Spacing Angles for Different Latitudes" table (Brown & DeKay, 2001), exemplary city, Seattle's recommended spacing angle is 45 degrees since the spacing ratio (H/W) should be in [0.4, 1.5] for the latitude of 46-48 degrees North. *Daylight envelope* is constructed as shown in Figure 4.6.

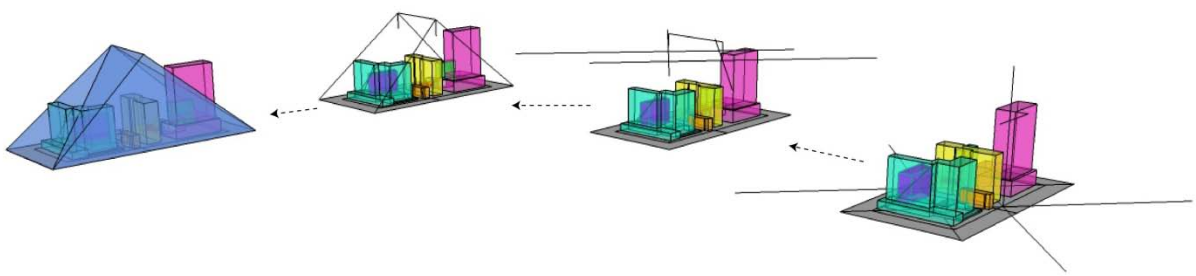

Figure 4.6. 3D Illustration of constructing Daylight Envelope for Seattle (latitude: 47.5 degrees North)

3. *Climatic Envelope*: Composite of Solar and Daylight Envelope

When solar and daylight envelopes are combined on the given site, *Climatic Envelope* only takes the common part where two envelopes overlap. Non-overlap envelope parts will be eliminated. As shown in Figure 4.7, there are significant variations on the shape of *Climatic Envelope* in different latitudes.

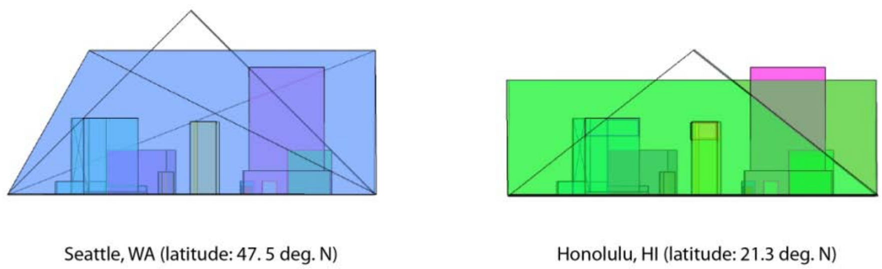

Figure 4.7. Elevation view of Climatic Envelopes of Seattle, WA and Honolulu, HI

Once *Climatic Envelope* is applied to the existing site, building volumes that are outside of the envelope are cut off. In Figure 4.8, the segmented building blocks are simplified as a rectangular box and are reconfigured into the building where the cut volumes have come from.

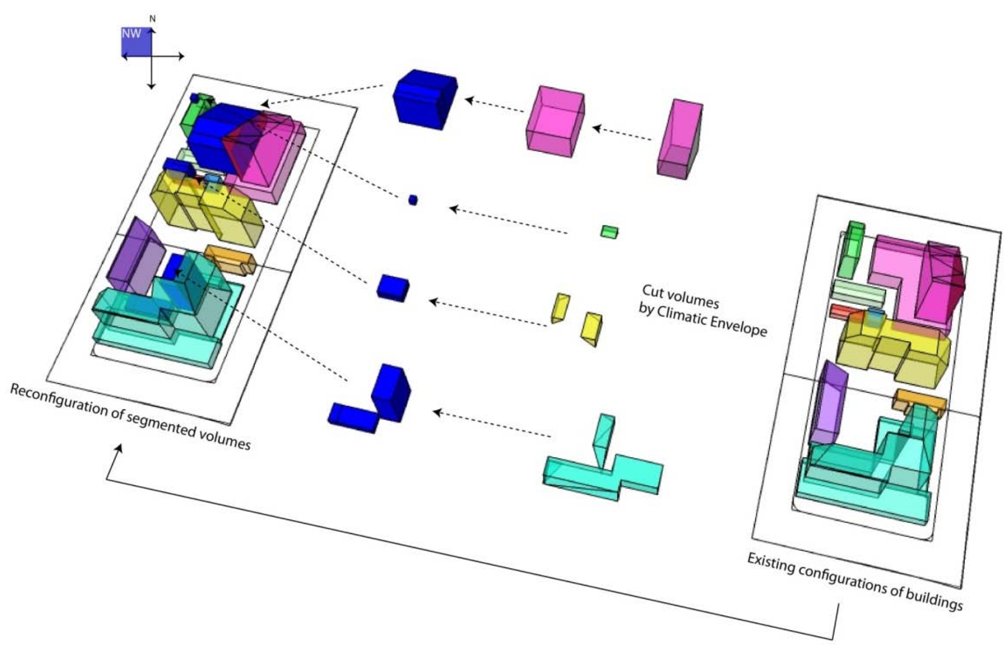

Figure 4.8. Reconfiguration of segmented volumes

There needs to be design rules that can inform how to configure the segmented buildings volumes and buildings themselves after the application of *Climatic Envelope*. Considering different sky conditions of various site locations, design rules should be articulated. The rules for configuration of buildings will be developed to achieve an average optimal visual comfort illuminance level under two representative sky conditions; clear and overcast sky.

4.3. Determining Dominant Sky Condition

Since the sky is changing in every minute of a day, designing for specific distribution of light is not feasible.[180] Therefore, average sky conditions are typically used for daylighting calculations.[181] Different models of virtual skies have been developed by the Commission International de I'Eclairage (CIE) and others. Although the CIE has mathematically developed 15 different sky conditions, two most representative average sky conditions are clear and overcast, which are illustrated as distribution of light in clouds form on the left and level of luminance on the right as shown in Figure 4.9. The meteorological definition of sky condition is "the predominant/average sky condition based upon fifth or more of either clear sky or overcast sky covered atmosphere."[182] They are widely used in daylighting simulations all over the world.[183] Consequently, the dominant sky conditions will be based on 50% of the average sky conditions, either clear or overcast in the given site.

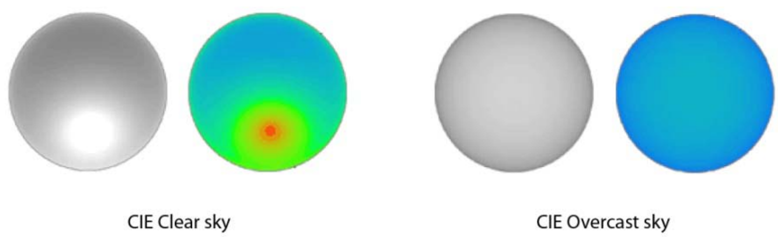

Figure 4.9. CIE Sky Conditions

CIE clear sky is the sky condition when there are no clouds or less than 30% of clouds covering the sky.[184] In a clear sky condition, the sky is assumed to be brighter towards the location of the sun, and the sun is visible. Direct sunlight has to be dealt with in this condition. The building models are tested under this condition to analyze the degrees of visual glare and thermal discomfort

[180] Sky Illuminance, Ecotect Community Wiki, accessd on February 5, 2013, http://wiki.naturalfrequency.com/wiki/Sky_Illuminance.
[181] Ibid.
[182] "Sky Condition," accessed on February 4, 2013, http://en.mimi.hu/meteorology/sky_condition.html.
[183] Kensek & Suk, Daylight Factor (overcast sky) versus Daylight Availability (clear sky), 4.
[184] Ibid.

in building performance. For predominated sunny climate areas such as Hawaii, Los Angeles and Phoenix, this sky model is considered in daylighting calculations.[185] Under CIE overcast sky condition, the sky is assumed to be covered by clouds in 100% so there is no visible sunlight. This sky model has been widely used to calculate daylight factor to measure adequate daylight access to buildings in a given site. The glare potential is less concerned in this sky condition since there is no direct sunlight. Many designers have used this model to calculate the worst lighting condition since it assumes there is no visible light. Daylighting simulation software such as Ecotect usually utilizes this sky model as a default, so the gradual improvement of daylighting condition of the built environment can be compared.[186] These sky conditions correspond to *Solar Envelope* and *Daylight Envelope* since they deal with different lighting conditions; direct sunlight and daylight. While direct sun light exists under clear sky condition, daylight exists in overcast sky condition.[187]

Although various regions have different sky conditions, current daylighting standards including *LEED (Leadership in Energy and Environmental Design) 2002/2009 Indoor Environment Quality 8.1* regard sky conditions for all regions uniformly. As different angles of the sun path impact the daylighting quality in buildings, sky conditions have significant influence to the building forms and their relationships.[188] Therefore, the sky conditions should not be treated equally in all regions. The evaluation of lighting quality should pursue the provision of visual comfort differently in these two dominant sky conditions (clear and overcast). The ways to achieve the satisfaction of the visual comfort and the absence of glare are different under these two sky conditions.[189] The illuminance level for visual comfort generally ranges from 300 to 2000 lux for various tasks and avoiding glare.[190]

4.4. Design Rules for Configurations of Buildings

According to the "Daylighting Report" by Illuminating Engineering Society (IES) (2012) and Knowles (1981), the implications of orientation, building placement and building form and size play a significant role in the effectiveness of daylighting. Design rules for configurations of buildings providing a thorough understanding of essential daylighting criteria should be created or re-designed under clear and overcast sky conditions. The rules are focused on generating optimal configuration that satisfies average visual comfort of buildings in an urban-scape. These synthetic rules are refined and simplified under dominant sky conditions. They can be applied in either a new site or an existing

[185] Kensek & Suk, 5.
[186] Kensek & Suk, 4.
[187] Brown & DeKay, 110.
[188] Brown & DeKay, 2001.
[189] Dubois, 8.
[190] "Daylighting Pattern Guide."

site design. The daylighting design criteria in the configurations of buildings are prioritized based on literature review and research experiments.

4.4.1. Experimental Model Parameter Setting

The setting of the experiment is based on existing urban design guidelines and daylighting design standards. Single building box volume is determined by building design guidelines from the Housing and Urban development coordinating council of the USA. The minimum floor area of a living unit in multi-family dwellings is 15' by 15' as shown in Figure 4.10.[191] The recommended height is 10'. The distance between two building volumes is also based on the standard distance from the building design guidelines. Typical alley and public walk ways are 6.5 feet.[192]

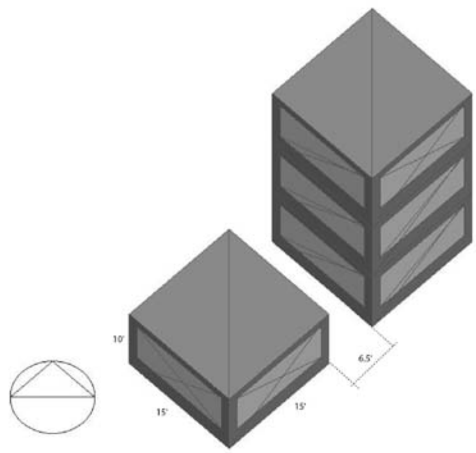

Figure 4.10. Basic Building Configuration Model

The setting for the time of a year is the September 21st Equinox, which is recommended by the 'Daylighting Pattern Guide,' developed by Advanced Building and Integrated Design Lab Seattle. This setting time is also standard for *LEED 2002/2009*. The illuminance levels of 9am and 3pm at Equinox were simulated through DesignBuilder. Shadow pattern from Ecotect shows overall sun impact in building geometric relations during Euqinox. In order to determine the appropriate location of tall buildings in relation to orientation, diagrammatic shadow pattern investigation and illuminance level analysis, the comparative studies of experiments' results were conducted during the study process. The opening/glazing condition is also set based on the 'Daylighting Pattern Guide.' The setting for openings is 60% of building façade area. The default setting for the windows includes a Solar Heat Gain Coefficient (SHGC), which is less than or equal to 6.5. Visible Light Transmission

[191] Housing and land use regulatory board, 35.
[192] Housing and land use regulatory board, 49.

Coefficient (VLTC) of the model windows is larger than or equal to 0.7. U-value of the windows is set as less than or equal to 0.45.[193]

Once a setting of single building configuration was established, a research experiment framework has been developed, as shown in Figure 4.11. With prototypical building forms for solar design; straight, angled and stepped forms,[194] the shadow patterns and average overall illuminance level of these different forms of buildings are analyzed in eight different orientations. The ratio for height differences in these three basic buildings forms is 3:1. Shadow patterns are investigated from Ecotect, and overall illuminance levels are simulated in the DesignBuilder software. Shadow patterns and overall illuminance levels are evaluated in eight different orientations, which are composed of the four cardinal directions and the four non-cardinal directions.

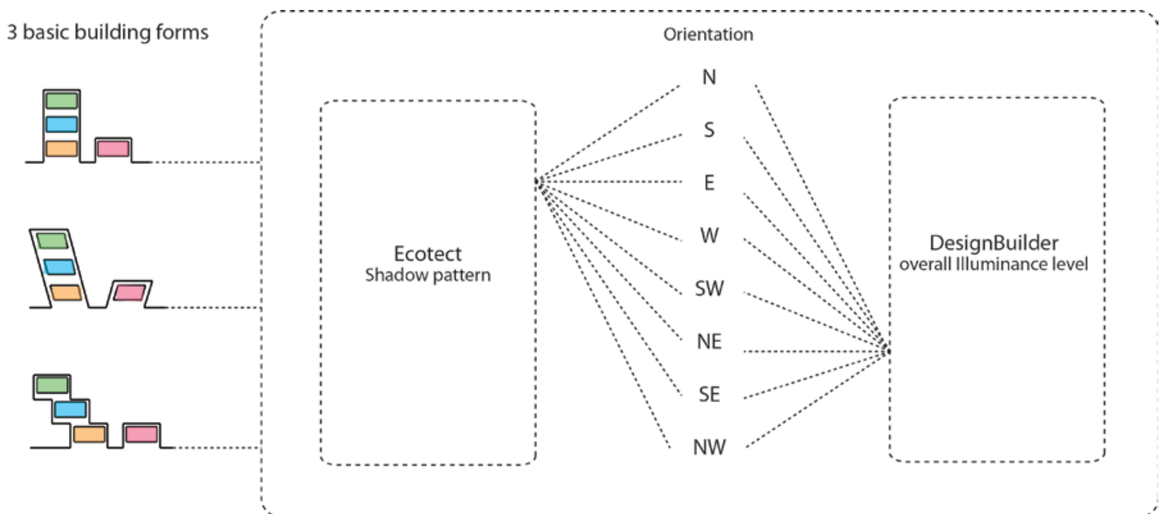

Figure 4.11. Research Experiment Framework

Under two dominant sky conditions, orientation, placements of buildings and building forms are explored. The results of basic configurations of buildings inform the preferred form and layout of buildings with difference under clear sky and overcast sky dominant conditions.

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193 State of Hawaii, Field guide for energy performance, comfort, and value in Hawaii Homes, 23.
194 Brown & DeKay, 2001.

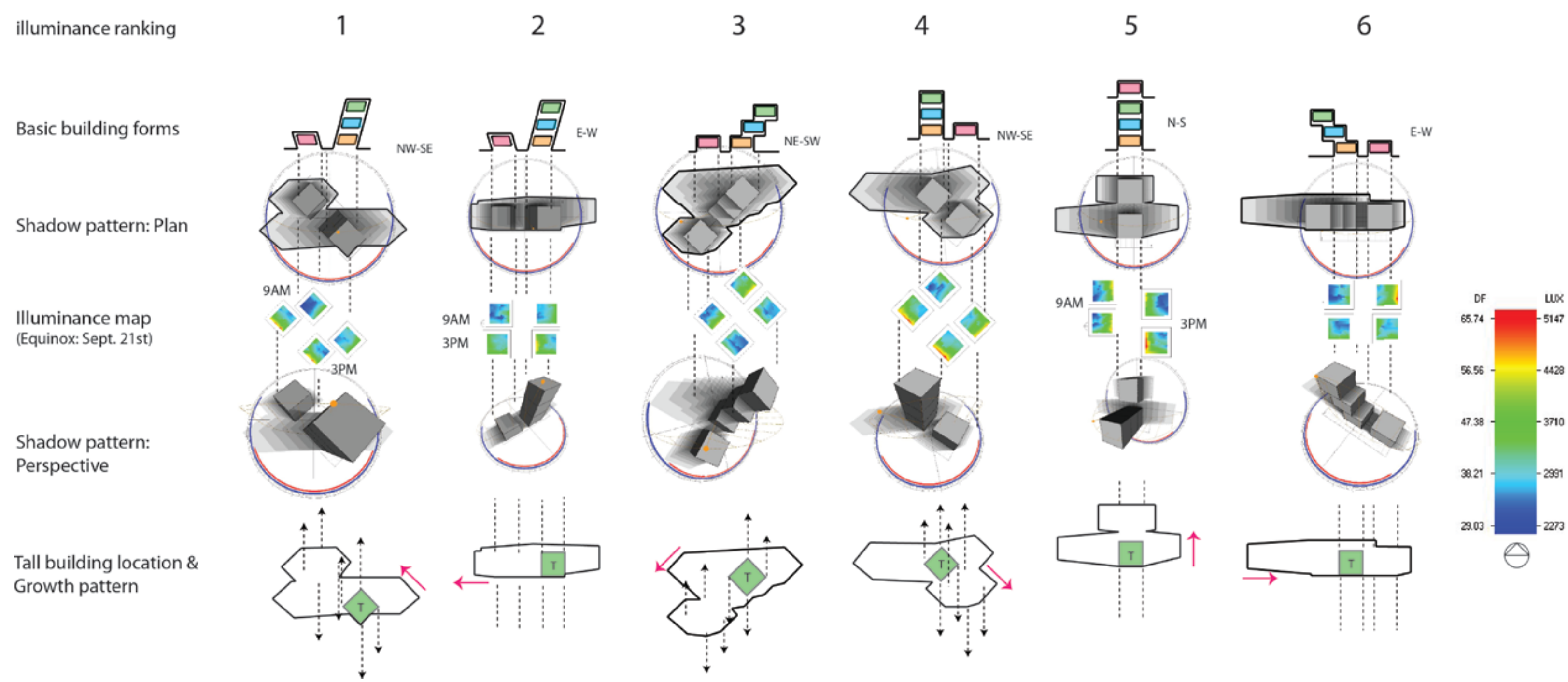


Figure 4.12. Basic Configurations of Buildings: Clear Sky condition

As shown in Figure 4.12, angled building forms are most preferred under clear sky dominant condition. The most preferred growth pattern of the buildings in this case is the southwest direction where tall buildings are located on the southeastern side. The non-cardinal growth pattern is also generally preferred rather than the cardinal growth pattern in a clear sky condition. Stepped building forms also provide an opportunity for a good visual comfort illuminance level when they are located on the southern side.

As shown in Figure 4.13, in overcast sky dominant regions, stepped building forms are most preferred in the design of an urban-scape. The most preferred growth pattern of the buildings is either the south or the northeast direction where tall buildings are located on the northern side. Building pattern growth in cardinal direction is favorable in this case. Stepped building forms generally provide an opportunity for a good visual comfort illuminance level. When the sun's location is very low in the winter sky, an angled urban-scape layout with the high south ridge increases the chance to maximize sun access into the space.[195]

[195] Knowles, Sun, Rhythm, Form, 155.

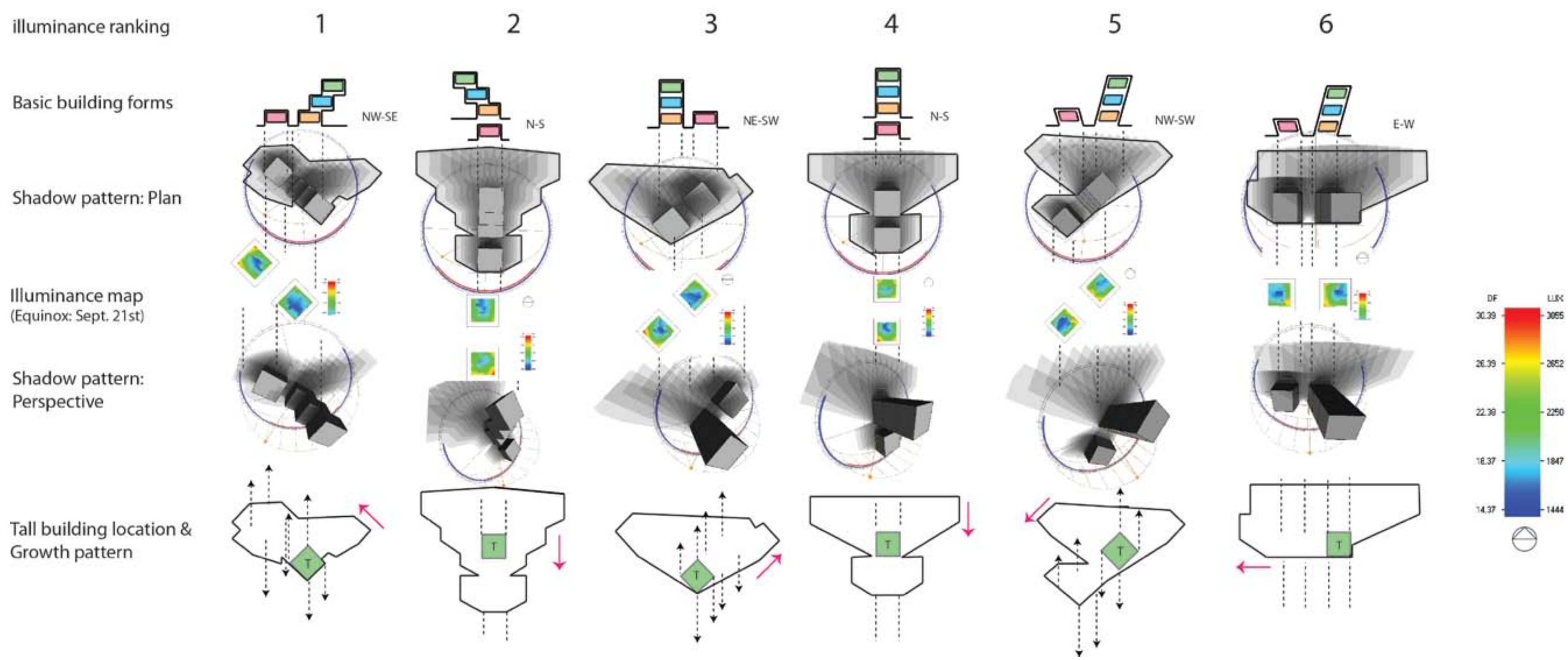


Figure 4.13. Basic Configurations of Buildings: Overcast Sky condition

4.4.2. Orientation of Building Growth Pattern

The orientation of buildings is crucial to mitigate excessive solar gain to interior environment.[196] Under both clear and overcast sky conditions, the most preferred growth pattern of the buildings is EW (East-West) direction, which maximizes the southern exposure so that more diffused light can enter the inside of the building, and the potential for glare can be reduced.[197] Depending on the given site's orientation, buildings should be situated properly to maximize southern exposure.

When the site is oriented in EW cardinal direction, the wide and the long side of a building should face the south. In this way, the interior space obtains ambient light that increases the level of visual comfort illuminance. As shown in Figure 4.14, under overcast sky condition, the buildings far apart are better than a short distance from each other. Because there is no direct sunlight access under overcast sky conditions, the plan should open as much as possible increase the light distribution of multiple buildings in the site. However, it is better to have short distance between rows of buildings under clear sky conditions because the buildings themselves shade each other from direct sunlight. Because the intensity of sunlight is minimized by a neighboring buildings' shadow, the overall ambient lighting quality reaches the level of visual comfort illuminance.

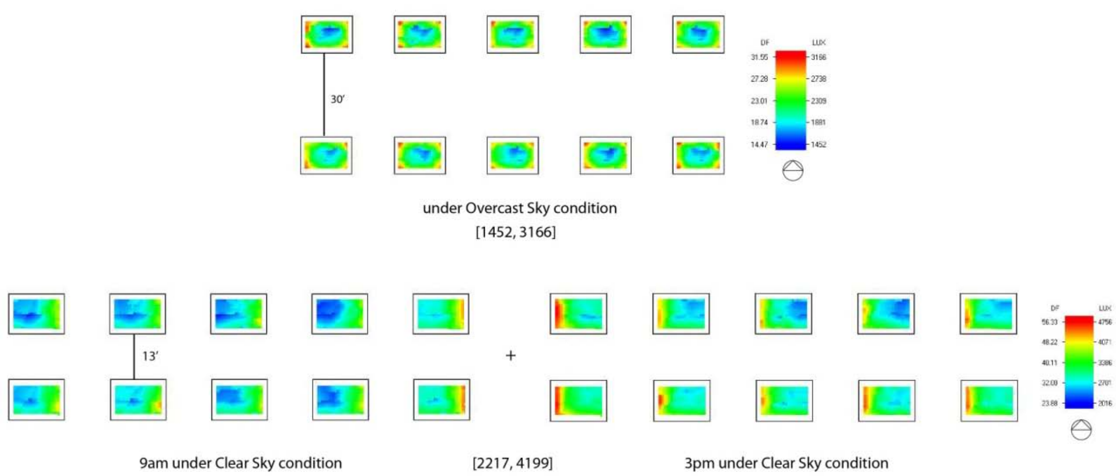


Figure 4.14. EW growth pattern (line-up): Illuminance map comparison under different sky conditions

Buildings in offset position work the best under an overcast sky than under a clear sky because it opens up the possibility for wider light distribution of the site as shown in Figure 4.15.

[196] Knowles, Sun Rhythm Form, 143.
[197] Hausladen, Climate Skin, 2008.

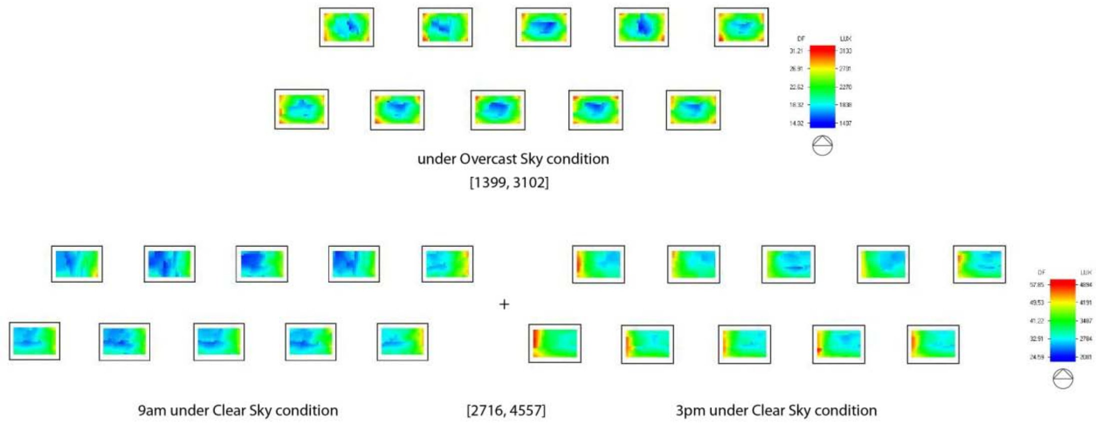


Figure 4.15. EW growth pattern (offset positioning): Illuminance map comparison under different sky conditions

When the site is oriented in NS cardinal direction, the opportunity for southern exposure is minimized compared to EW orientation, so offsetting the buildings is the most effective way to increase the visual comfort illuminance level for both overcast and clear sky conditions as shown in Figure 4.16.

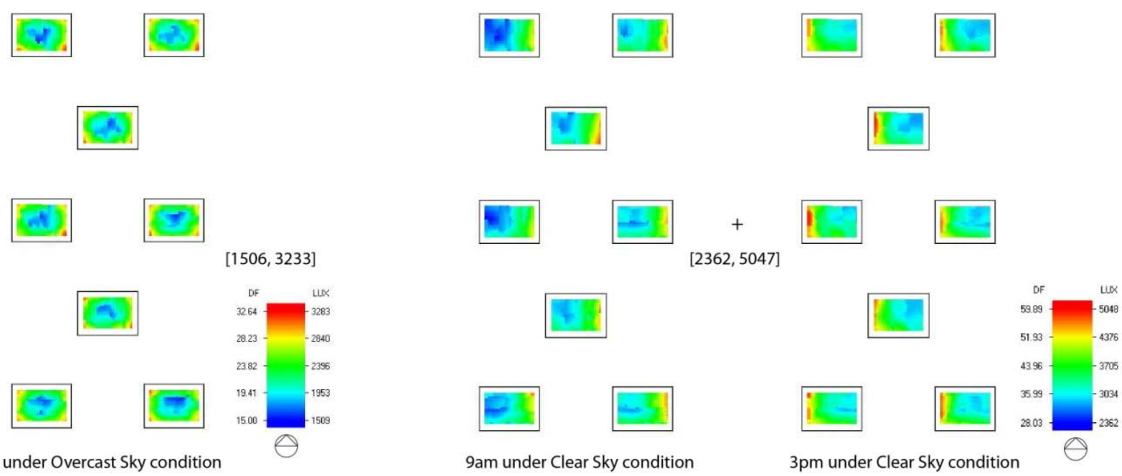


Figure 4.16. NS growth pattern: Illuminance map comparison under different sky conditions

Under non-cardinal orientation, preferred building development orientation is same for both sky conditions. In order to maximize southern exposure, it is best to orient all the buildings in offset manner although the site is angled. In NE-SW orientation, the layout of multiple buildings is oriented in similar way with the buildings' positions from NS orientation (Figure 4.17). However, in NW-SE orientation, orienting the buildings following the site form provides a better average visual comfort illuminance level as shown in Figure 4.18.

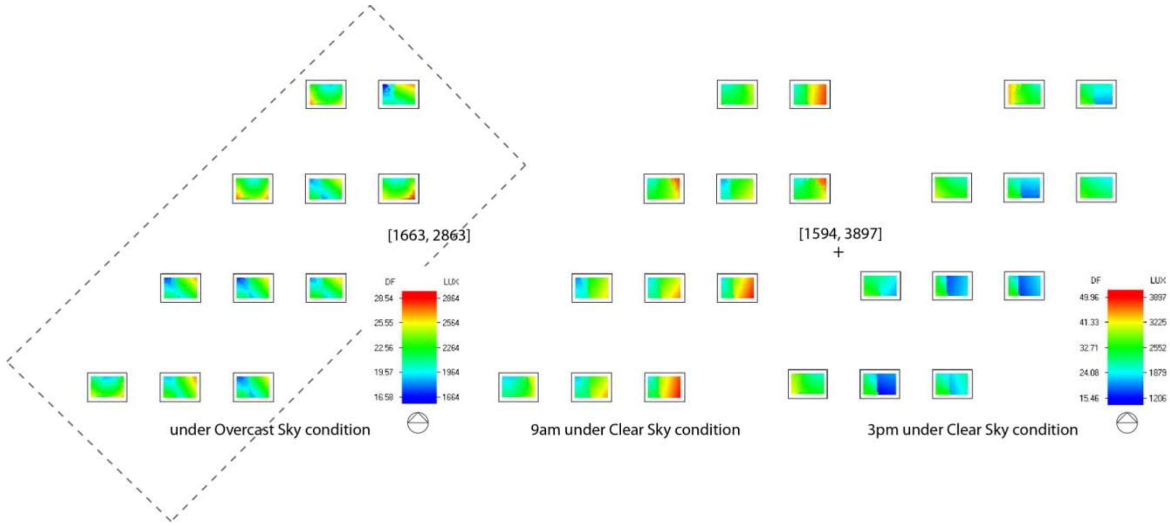


Figure 4.17. NE-SW growth pattern: Illuminance map comparison under different sky conditions

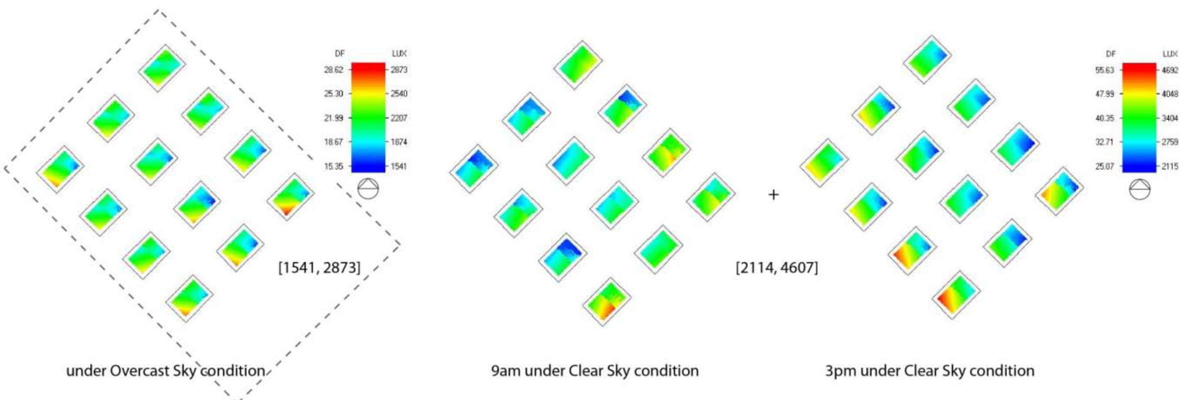


Figure 4.18. NW-SE growth pattern: Illuminance map comparison under different sky conditions

Under non-cardinal orientation, preferred building development orientation is same for both sky conditions. In order to maximize southern exposure, it is best to orient all the buildings in offset manner although the site is angled. In NE-SW orientation, the layout of multiple buildings is oriented in similar way with the buildings' positions from NS orientation (Figure 4.17). However, in NW-SE orientation, orienting the buildings following the site form provides a better average visual comfort illuminance level as shown in Figure 4.18.

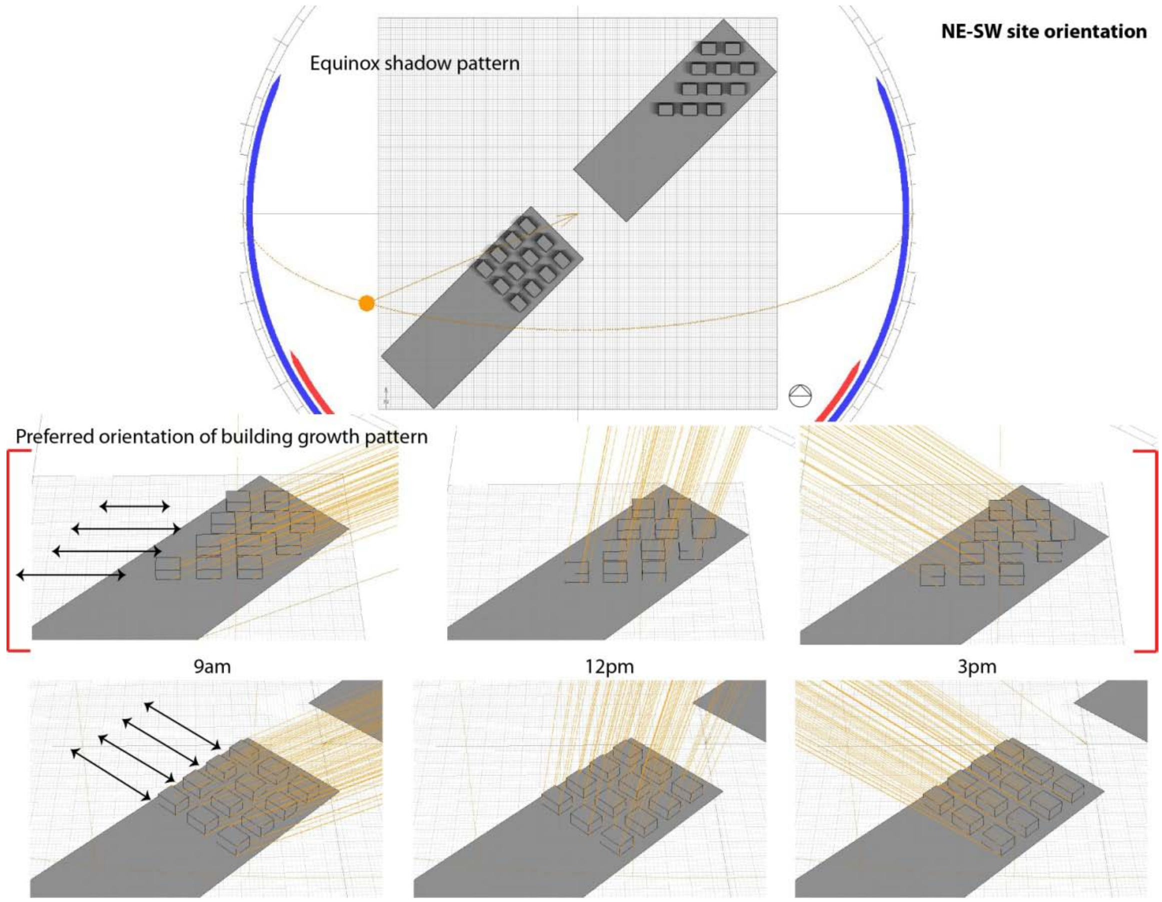


Figure 4.19. Variation: Orientation of buildings in NE-SW site (clear sky condition)

This is because of the relationship between the surface orientations of building volume and sun path under different sky conditions. As shown in Figure 4.19, sunray study shows that the percentage of sunlight exposure to the building surfaces is same for both building growth direction in NE-SW site orientation. There were only 2% average illuminance level between these two building growth pattern, so the pattern can be either in this case.

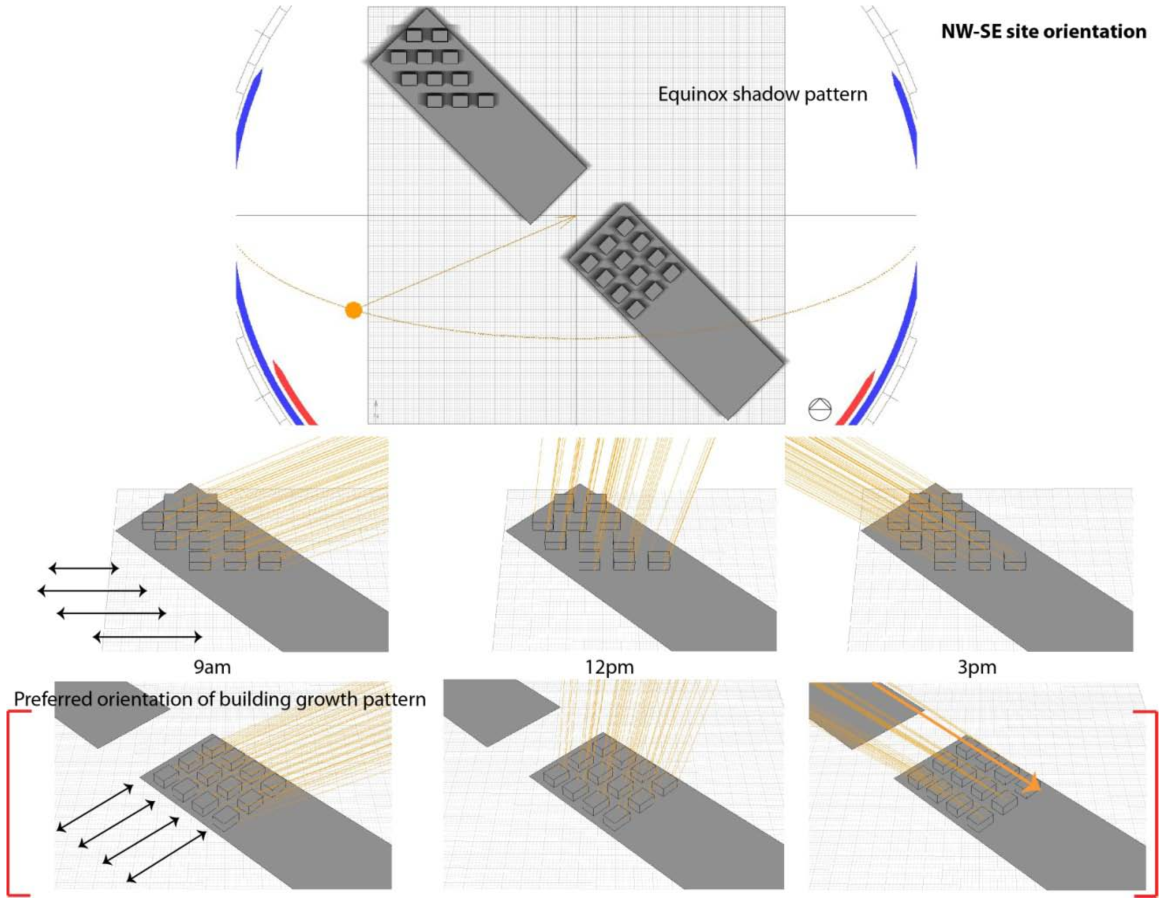


Figure 4.20. Variation: Orientation of buildings in NW-SE site (clear sky condition)

However, the building growth pattern, which follows the site form, has less direct sunlight access in sunray study at 3pm as shown in Figure 4.20. Its average illuminance level is 20% closer to visual comfort illuminance level standard. Therefore, for NW-SE site orientation, the building growth pattern that follows the non-cardinal site form is preferred.

Since the angle of the sunlight on the south facade is steep, the intensity of sun's radiation is less compared to the other side.[198] Therefore, maximization of the southern exposure of buildings is the key to design a multiple building growth pattern for minimizing the potential for glare. The general growth pattern of buildings in both cardinal and non-cardinal site orientation is demonstrated in Figure 4.21.

[198] Hausladen, Climate Skin, 40.

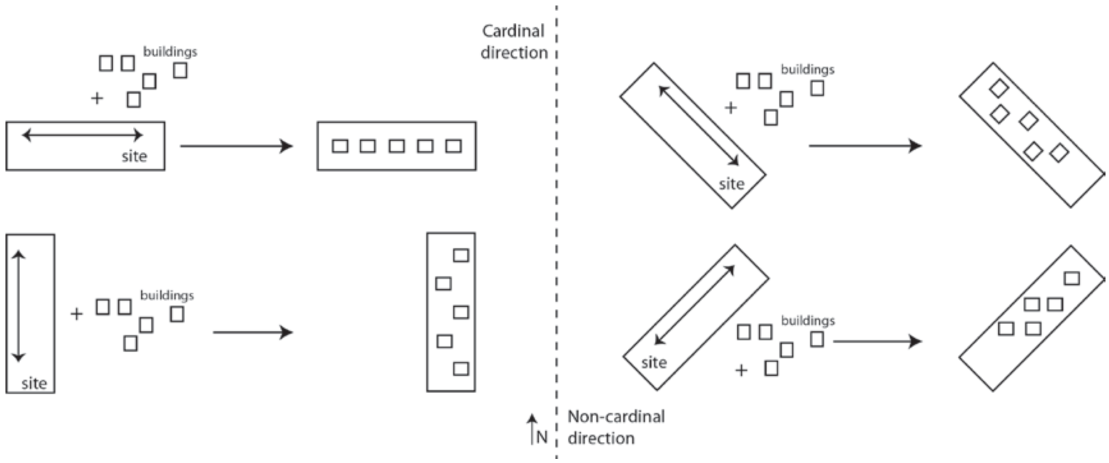


Figure 4.21. Buildings' general growth pattern per sites' orientation

4.4.3. Placements of Buildings

4.4.3.1. Placement of buildings with general building height difference

Although a given site is sometimes situated with difficult natural light access, the juxtaposition of buildings can mitigate the effects of the natural variation of sunlight.[199] For both clear and overcast sky conditions, the EW cardinal layout creates potential for a good visual comfort level.

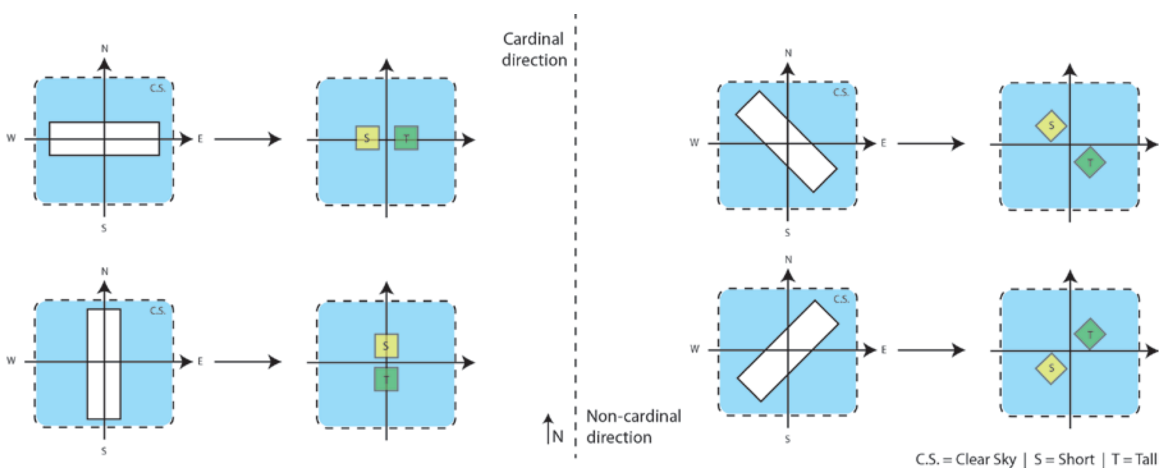


Figure 4.22. Basic Placements of Buildings: Clear Sky condition

[199] Knowles, Sun Rhythm Form, 144.

The design rules for the placements of buildings under clear sky condition are: 1) when the buildings are located on EW growth, place short buildings on the west side, 2) when the buildings are situated in NS (north-south) cardinal growth, place short buildings on the north side, 3) if the site is oriented in NW-SE direction, short buildings should be placed on NW side, 4) short buildings are better to be placed on SW side when the buildings are non-cardinally oriented in the NE-SW direction, 5) compact and closed configuration of buildings work better to achieve visual comfort illuminance level under clear sky conditions because the buildings can be a shade to each other which lowers the potential for glare issues and direct sunlight, and 6) When the building surfaces are overlapped, it is better to have tall building surfaces face either north or south. Based on the illuminance level ranking under clear sky, the relationship of building placements in height difference is illustrated in Figure 4.22.

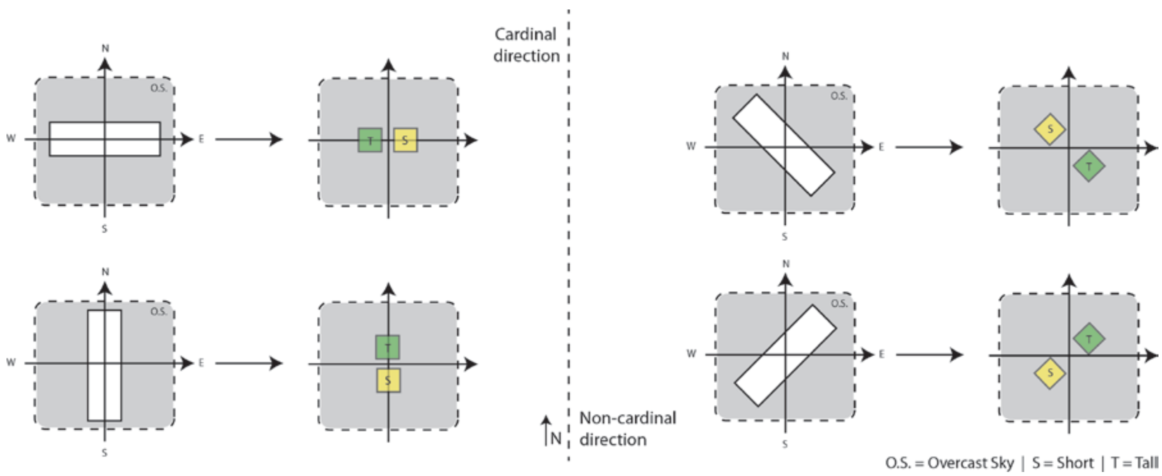


Figure 4.23. Basic placements of buildings: Overcast Sky condition

Also, the design rules for the placements of buildings under overcast sky conditions are: 1) For cardinal direction, short buildings are better to be placed in the east side when the site is in the EW growth, 2) When the site is in the NS growth, short buildings should be placed on the south side, 3) building location with general height difference in a non-cardinal site is the same for both dominant sky conditions, and 4) especially in winter time, non-overlap and the open layout of the buildings are preferred to maximize the sun access to short buildings. The summary of building placements based on relatively high visual comfort illuminance level under overcast sky is shown in Figure 4.23.

4.4.3.2. Relationship between Building height and distance

When buildings are clustered in an urban setting, the relationship between building heights and distance becomes a critical factor in visual comfort. Considering the profile angle of the low altitude winter sun and high altitude summer sun, the appropriate distance between buildings can be determined.[200] The relationship between building height and distance is shown in Figure 4.24. Having building height H and distance between buildings d as direct relationship, d = x (H), when the factor of this relationship x is between min: 2.5 and max: 5.4, buildings have adequate sunlight access in overcast sky dominant condition. For a clear sky dominant condition, x is ranged between min: 0.8 and max: 1.3. While the minimum number x represents the high profile of the sun during the day time, the maximum number x indicates the low profile of the sun in the early morning and late afternoon. This is because sun in the early morning and late afternoon is in a relatively in low position of the horizon, so in order to increase the sun access and avoid shadow, the buildings should be farther apart than when the sun is in high position. In summary, distance factor x=[0.8,1.3] is ideal for clear sky condition, and distance factor x is x=[2.5,5.4] under overcast sky condition is theoretically desirable. The relationship between building height and distance cannot be idealized at all times in reality because of given site dimension restriction, so the placement of buildings with building shape and orientation should be considered simultaneously in finding the optimal configurations of buildings.

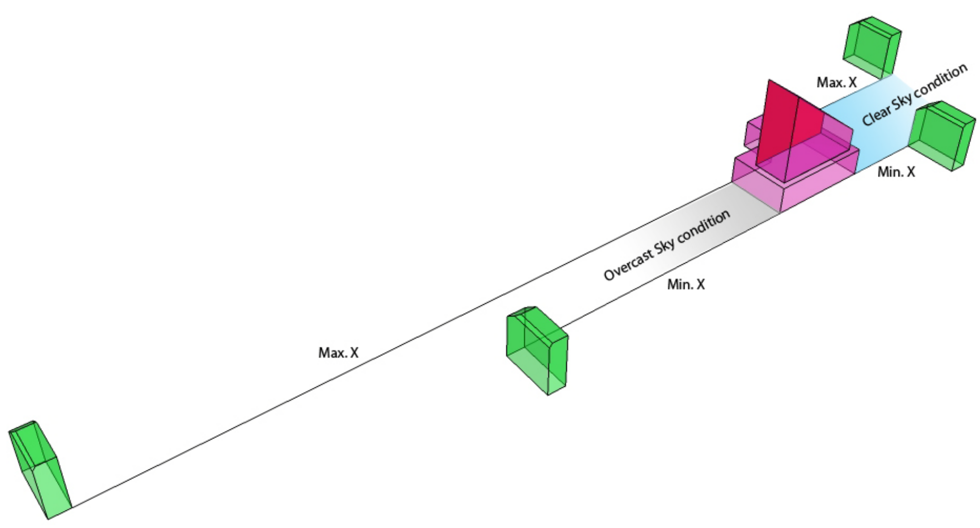


Figure 4.24. Maximum and minimum factor x for the relationship between building height and distance in overcast sky and clear sky conditions

[200] Brown & DeKay, Sun, Light, & Wind, 2001.

4.4.4. Building Form and Size

The form of building plays a significant role to control sunlight access.[201] Transformation of the building is essential to establish better environmentally fit relationship among interrelated buildings around.[202] Prototypical building forms for solar design are straight, angled and stepped forms.[203] Stepped building forms are preferred in overcast sky conditions because stepped surfaces allow sunlight to be reflected off of the front horizontal surfaces which can bring indirect and diffused light into interior spaces such as light shelf effect[204] as shown in Figure 4.25 and 4.26.

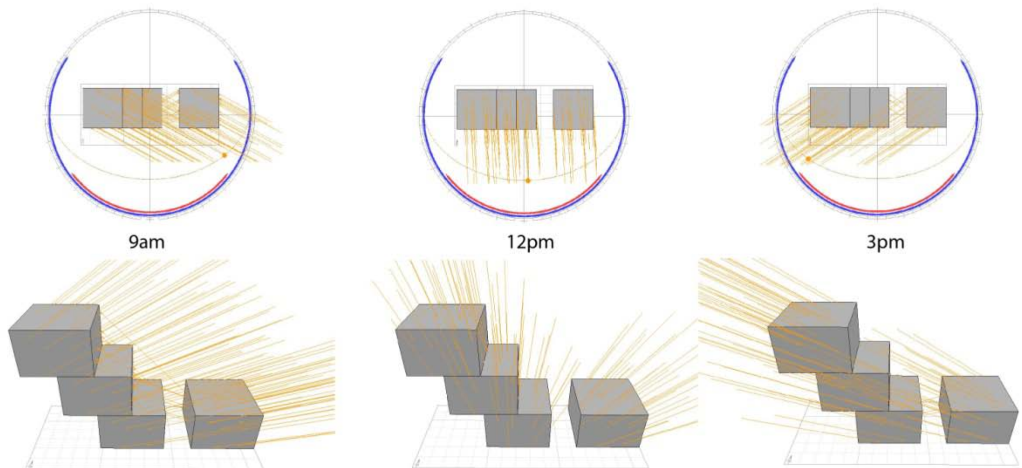


Figure 4.25. Stepped building form in Cardinal direction during Equinox

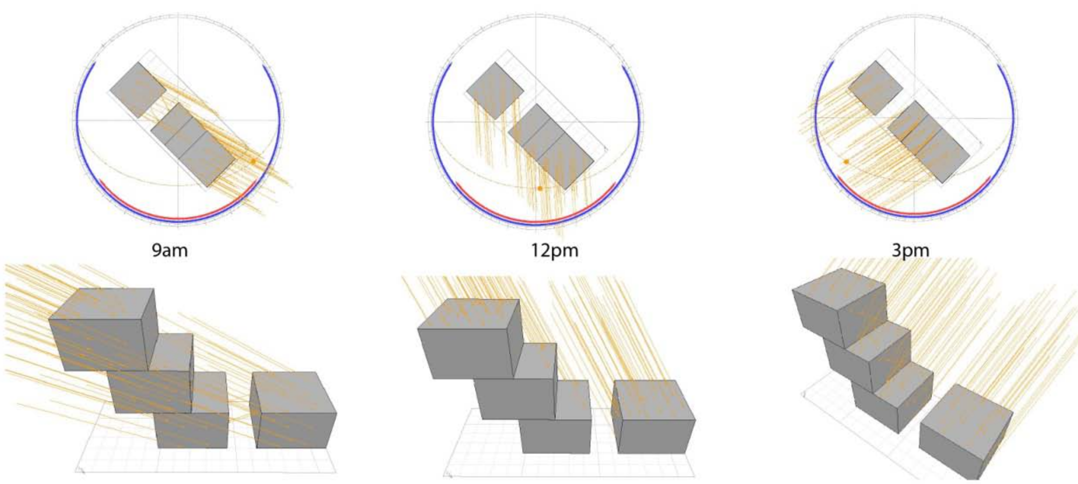


Figure 4.26. Stepped building form in Non-Cardinal direction during Equinox

[201] Rakha & Nassar, 2010.
[202] Knowles, Sun Rhythm Form, 145.
[203] Brown & DeKay, Sun, Light & Wind, 2001.
[204] Ibid.

Angled building forms are preferred in clear sky conditions with a 30 degree slope. However, the degree of building slope between 15 and 60 is acceptable for creating an adequate visual comfort level. There can be three different layout options for the angled building form; opened form, closed form, and parallel form. Under 30 degree slope, these three forms are tested in terms of illuminance level. The results have shown that parallel form is the most appropriate for cardinal orientation of buildings. For non-cardinal orientation, the open form has created optimal visual comfort illuminance level. Preferable building forms under each dominant sky condition are shown in Figure 4.27 and Figure 4.28.

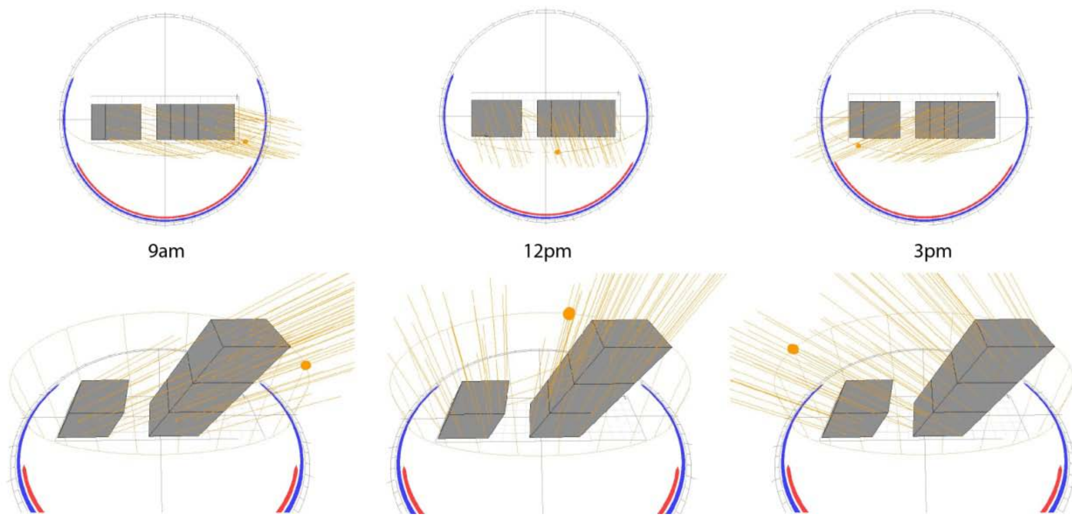


Figure 4.27. 30 degrees angled building form in Cardinal direction during Equinox

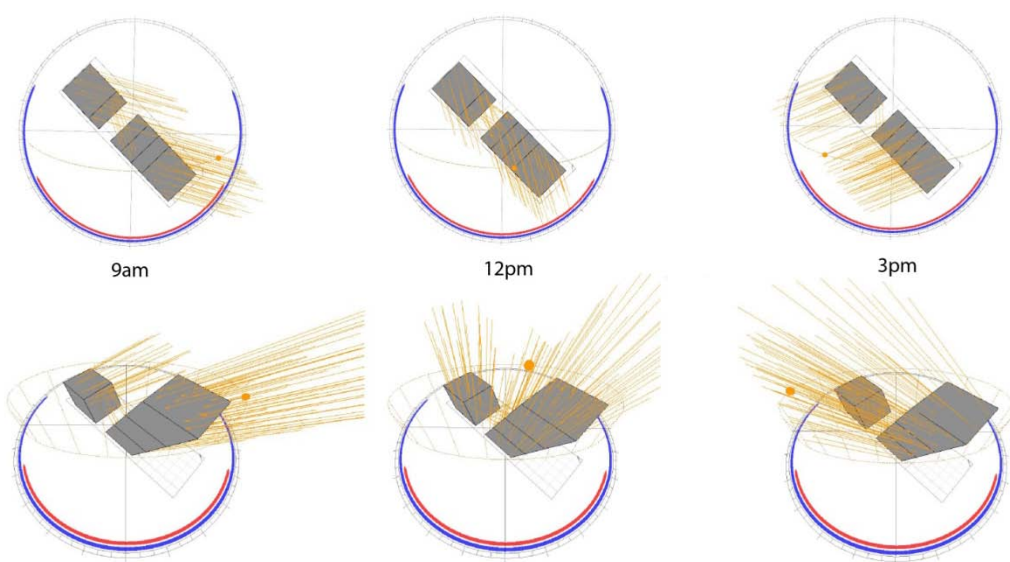


Figure 4.28. 30 degrees angled building form in Non-Cardinal direction during Equinox

As shown in Figure 4.29, angled building form is appropriate for clear sky conditions because the angled surfaces avoid direct sunlight access into the interior. Another benefit of an angled form is that the travel distance of reflected light from one surface to the surface of other building is longer than straight building so that more diffused light can be seen than the direct light onto other building's surface.

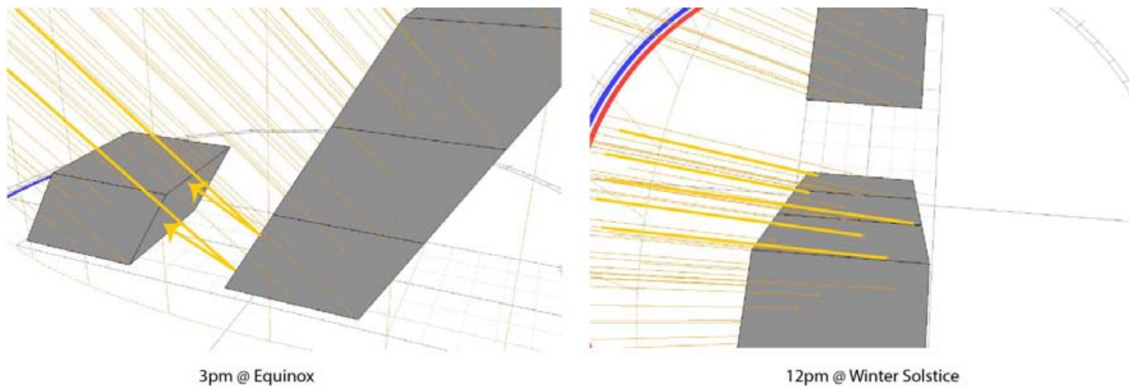


Figure 4.29. Sunray study for angled building form

Stepped building can create an interior/exterior light shelf effect as a building level. As shown in Figure 4.30, the horizontal surface in the front of building openings can act as light shelf that can reflect the direct light into the space as diffused light. The amount of reflected light can be adjusted based on the area of horizontal surface or the size of the openings. This building form can be good for both clear sky and overcast sky conditions because it can mitigate direct sunlight but also it can draw much ambient light into the space.

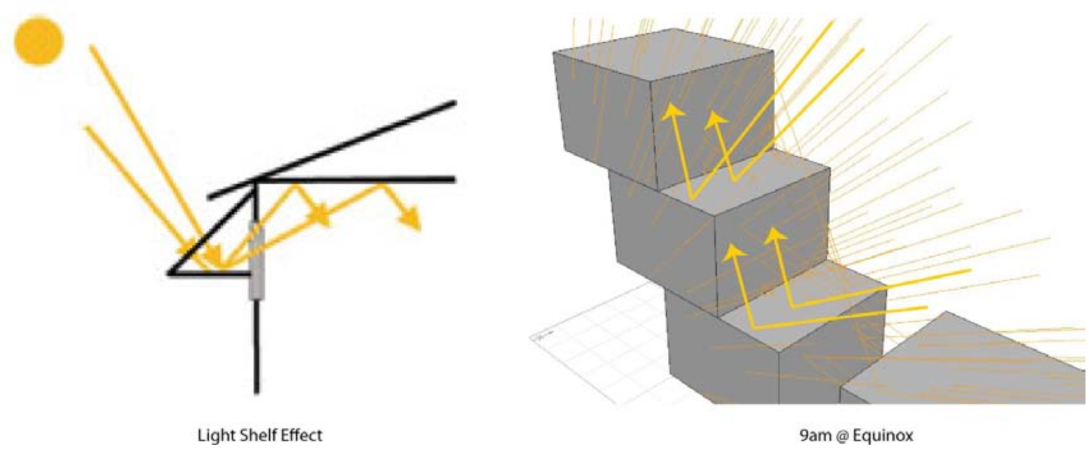


Figure 4.30. Sunray study for stepped building form

The illuminance resulted from the comparison between segmented building blocks and a building as a whole clearly shows that a building's size affects the relationship between a building's exposed surfaces and its volume.[205] Segmented buildings provide better opportunities for visual comfort lighting than one big mass building because of the reduced susceptibility of large buildings to external variations.[206] The speed of the response to environmental change is much slower in large buildings than smaller buildings. The illuminance level differences from building size and volume changes are demonstrated in case studies. The relationship among building form variations, their shadow pattern, and placements of building with height difference is summarized in Figure 4.31.

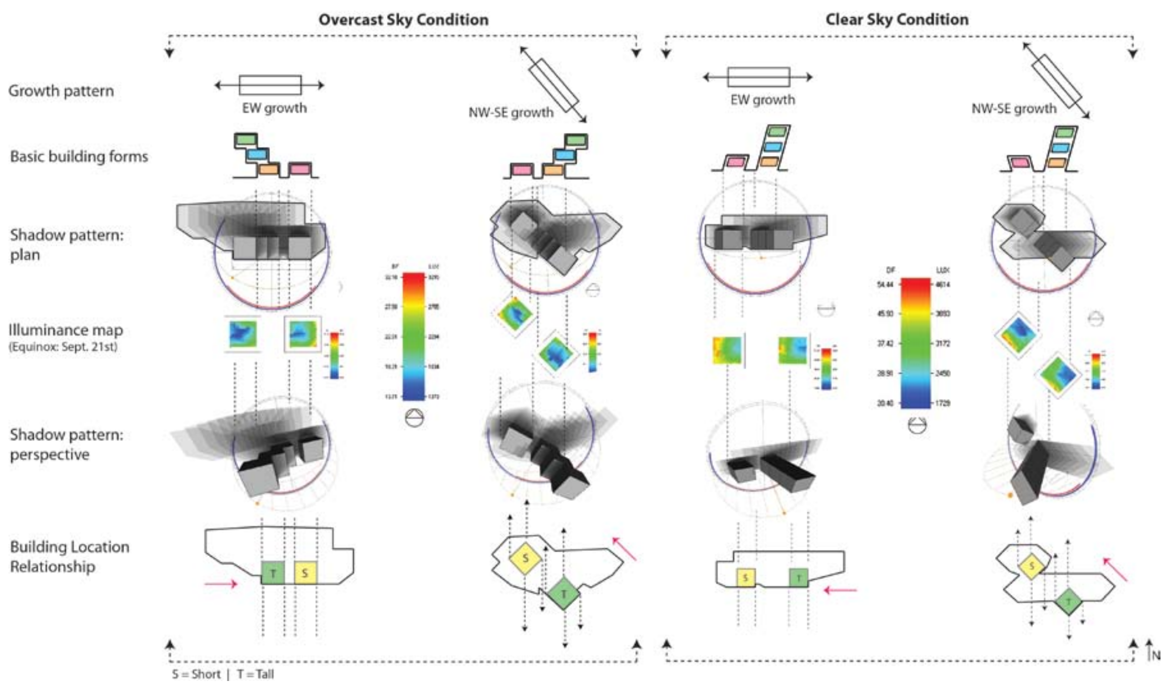


Figure 4.31. Building form Overview: Overcast Sky condition vs. Clear Sky condition

[205] Knowles, Sun Rhythm Form, 145.
[206] Ibid.

4. 5. Integrated Daylighting Design Procedure

The following design rules take basic configurations of a building's summary as an initial point to prioritize and organize essential components in synthetic design process with natural light. These rules can be applied to either brand new sites or existing sites. The key components; 1) orientation, 2) placements of buildings, 3) building forms and size are formatted to guide designers for creating appropriate configurations of buildings under dominant sky conditions of any given sites.

Let the site location be given.

Procedure 1: collecting necessary information for constructing 3D boundary.

P 1.1: Find the latitude of the site.

P 1.2: Find the orientation of the site.

- Cardinal orientation:
- Non-cardinal orientation:

P 1.3: Find the dimension of the site.

P 1.4: Find tallest building height and the given street width between given site to other parcels.

Procedure 2: Constructing 3D boundary

P 2.1: Construct Daylight Envelope over the site in the EW direction.

P 2.2: Construct Solar Envelope over the site in the NS direction.

P 2.3: Take only overlapping envelope of Rule 5 and Rule 6.

Calculating the volume of cut building blocks: The cut building block volume should be figured out in a simplified form so that building volumes can be configured back into the building where cut volumes are from as shown in Figure 4.32. This procedure happens whenever *Climatic Envelope* is applied.

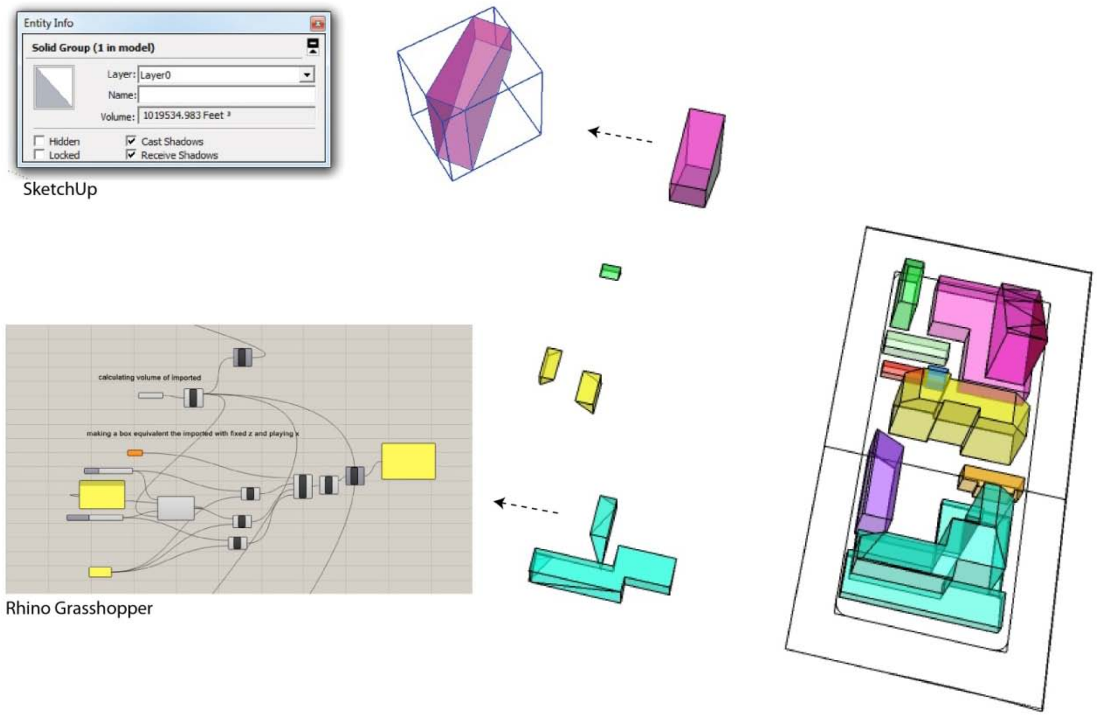


Figure 4.32. SketchUp & Rhino Grasshopper script for calculating cut volumes

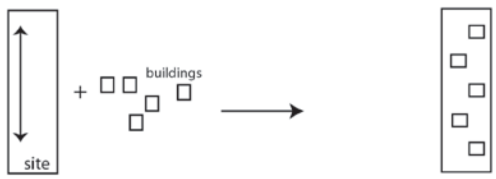
In this process, "entity info" tool in Ecotect can be used to figure out the cut building part volumes. Sometimes, Ecotect's "entity info" cannot provide the volume information because of block's surface closing issues. In order to overcome this challenge, Grasshopper script working with Rhino is programmed. From this Grasshopper formula, volumes of any geometric shape can be found once they are imported to Rhino. Then, the volumes are reconfigured as rectangular forms to fit in the building where corresponding cut volumes are from. Rectangular building forms are easy to be integrated with existing buildings, and it provides more flexibility to change fitting into the existing buildings. The most important point here is to keep 1:1FAR (Floor Area Ratio). While the FAR is the same in the variations, "the characters of the buildings and site plans can be very different."[207]

[207] Pollacks, What is Floor Area Ratio (FAR), 1.

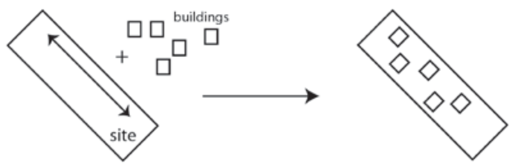
Procedure 3: Determining the orientation of multiple buildings' growth pattern

P 3.1:

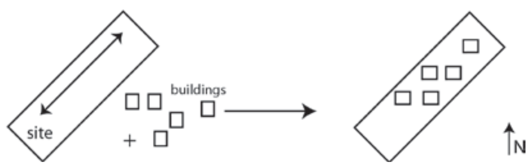
P 3.2:



P 3.3:



P 3.4:



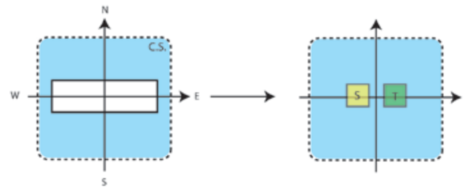
Procedure 4: Determine the dominant sky condition of the site.

P 4.1: If selected site has 50% or more clear sky condition throughout a year,

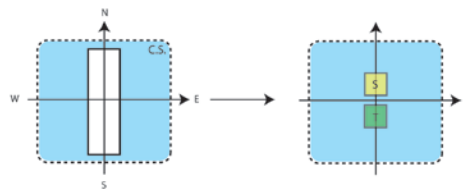
P 4.2: If selected site has 50% or more overcast sky condition throughout a year,

Procedure 5: basic building placement

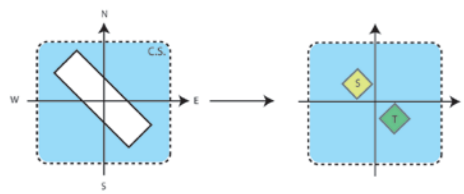
P 5.1:



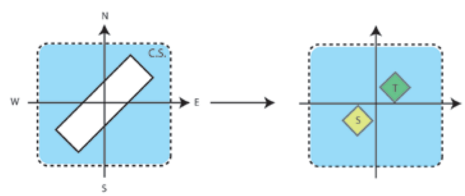
P 5.2:



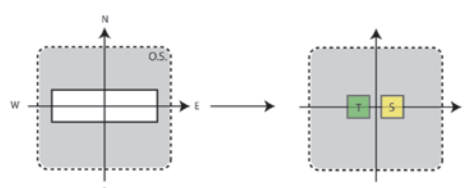
P 5.3:



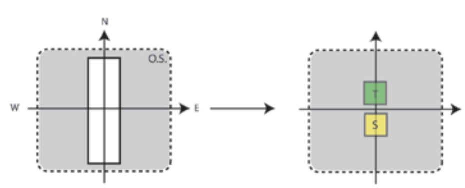
P 5.4:



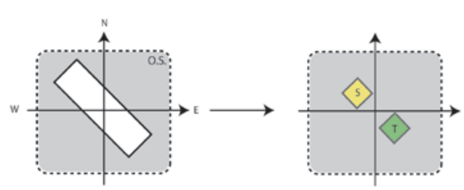
P 5.5:



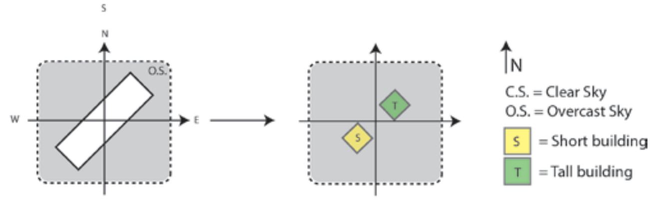
P 5.6:



P 5.7:



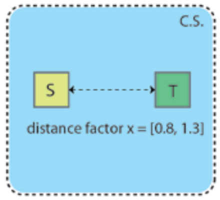
P 5.8:



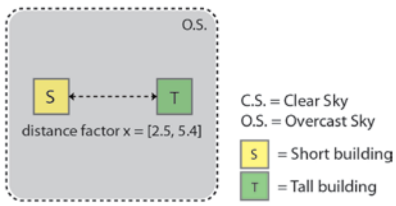
Procedure 6: Building height difference and distance

Given direct relationship, d=x(h) where d=distance between buildings, x=distance factor, h=building height,

P 6.1:



P 6.2:



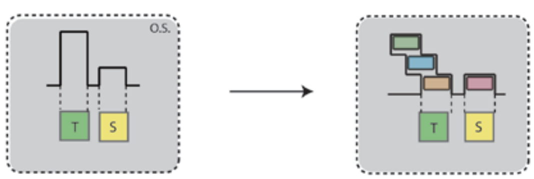
Procedure 7: Building form

The degree range between 15 and 60 is acceptable.

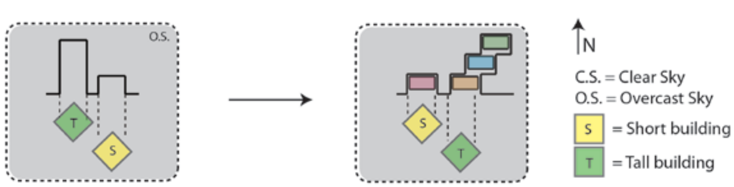
P 7.1:

P 7.2:

P 7.3:



P 7.4:



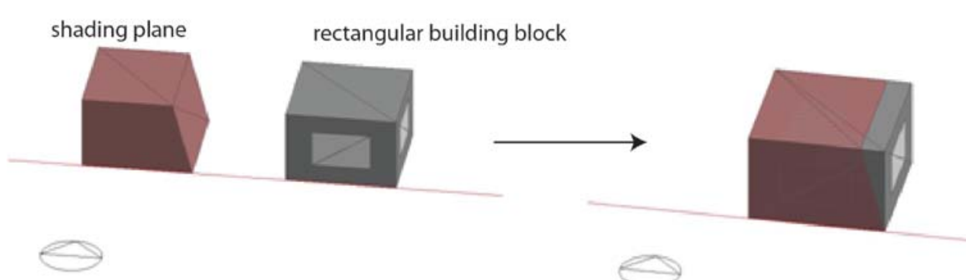
Throughout the integrated procedure of the configurations of buildings, three assorted computer programs are utilized. They are SketchUp, Ecotect, and DesignBuilder. The following procedure is the description of how to make transitions (import and export) among these softwares. SketchUp is for initial building modeling, while Ecotect and DesignBuilder are for analyzing and simulating shadow patterns and illuminance map/table. By synchronizing these softwares, one can obtain the information about the daylighting performance of building models.

- SketchUp to Ecotect

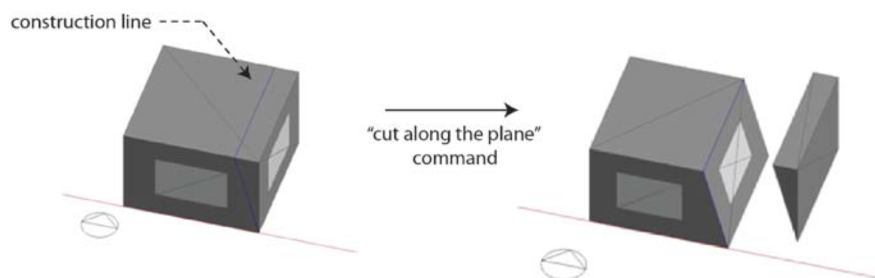
1. Make sure to make geometry as a group first in Sketchup.
2. Export the sketchup model as "export – 3D model – Export type: 3DS file – Options: Export: Full hierarchy (make sure that scale: feet)"
3. Then, open up the Ecotect and import the 3DS model as "import – 3D CAD geometry – Files of type: 3D studio – make sure to click "remove duplicate faces" and "auto merge triangles" – Also, make sure to change "scale objects by: feet to millimeters" – select all the zones – "zone – by item name" – "import into existing."

- Ecotect to DesignBuilder

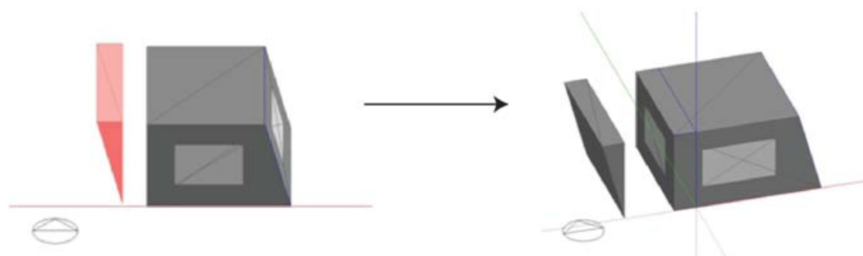
1. Export the Ecotect file to "to external analysis tool" with file type: gbxml
2. Import the gbxml file into Designbuilder as "3D CAD model."
3. Unfortunately, the model comes in as shading plane, so it is required to rebuild the model.
   - Rebuilding a model in DesignBuilder
   1. Overlap rectangular building block onto the shading plane geometry. The building block will be cut into the shape of shading plane geometry so that the illuminance level of the building can be simulated.



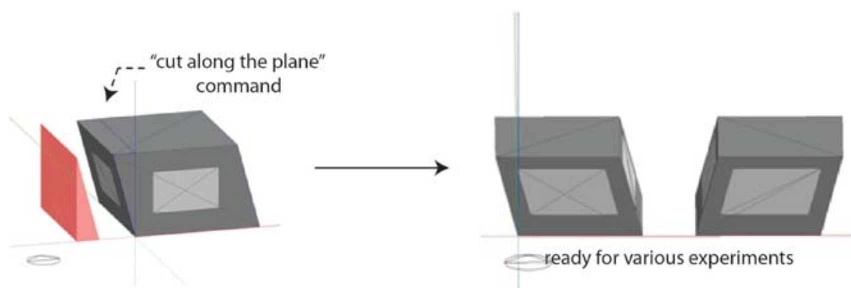
2. Draw construction line on the box model, indicating where the angle cut line is.
   - Erase all the shading planes on the model.
   - Do "cut along the plane" on the model.



3. Bring the cut block on the backside of the model.
   - Measure the length of the cut block, and then set it aside for now.
   - Drag the backside of the model by the length that is measured in the previous step.



4. Do "cut along the plane" on the model. Then, the model is ready for various experiments by changing orientation, placements of buildings and building forms.



5. DAYLIGHTING SYNTHESIS STUDIES

5.1. Site Setting

The proposed daylight design framework is applied to the urban block design of a selected site under clear and overcast sky conditions. The chosen project city block is in Honolulu, Hawaii. The chosen project area is one of Waikiki's hotel sites. The site has a combination of buildings with different heights, so it can provide multiple variations that lead to interesting optimal configuration of buildings that satisfies visual comfort illuminance level.

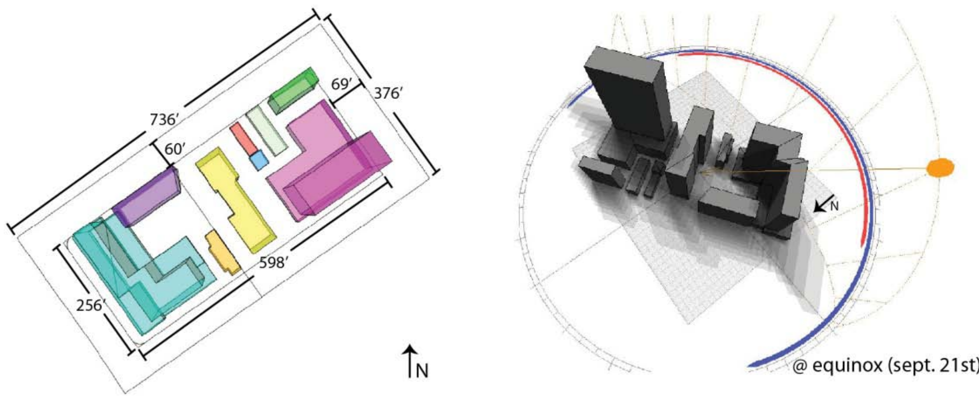


Figure 5.1. Selected Site's dimensions and shadow pattern for Variation Study

The buildings in this site are conventionally rectangular buildings as shown in Figure 5.1. On the plan, the overall building layout a relatively is closed form. Buildings are color-coded for identifying different building volumes. There is slight open space between the Sky-blue (SkyB) building and the Yellow building. The site is oriented in a NE-SW non-cardinal direction. There are two tall buildings, the Pink building is located on northeast side, and the SkyB building is on southwest side. The Pink building's large surface faces the south side.

The dimension of the actual building site is 256' by 598'. However, in order to construct a 3D boundary condition, the street widths to other buildings and total buildable dimensions should be identified as in Figure 5. The existing building layout is a relatively closed form. The buildings in this site are conventional rectangular forms with various heights and volumes. The Pink, Yellow and SkyB buildings are tall, and have large building volumes on this site. The rest of the buildings have relatively low heights. Based on the Integrated Procedure, Procedure 1 can be identified as the following.

P 1.1: Honolulu's latitude is 21.3 degrees North, and Seattle's latitude is 47.5 degrees North.

P 1.2: The site is non-cardinal orientation with the growing pattern in NE-SW direction.

P1.3: As shown in Figure 5, the dimension of the site is 256' by 598'.

P1.4: The height of the tallest buildings in the given site is 254'. The street width in NE-SW direction is 69', and the street width in NW-SE direction is 60'.

The profiles of the buildings in a given site are identified as the following (Table 5.1):

Buildings	**Height (feet)**	**Volume (cubic feet)**
Green (G)	89	230,081
Purple (P)	89	502,806
Light Green (LG)	26	24,812
Red (R)	17	23,390
Blue (B)	26	21,415
Pink (P) (composed of 2 volumes)	Base: 47 Upper: 207	Base: 165,787 Upper: 1,865,805
Yellow (Y)	145	1,303,198
Sky Blue (SkyB) (composed of 2 volumes)	Base: 25 Upper: 127	Base: 401,671 Upper: 1,493,119
Orange (O)	44	109,654

Table 5.1. Profiles of buildings on a selected site

Then, *Climatic Envelope* is applied to set the 3D boundary condition for each site. According to configurations of the building's guide, the site is gone through the investigation of 1) location, 2) placements of buildings and 3) building form and size. Lastly, the varying results are compared and analyzed to verify the application of the Integrated Procedure.

.

5.2. Clear Sky Condition

Honolulu has 271 days of sun out of a year, so 74% of the year in Honolulu has clear sky.[208] The site in Honolulu is considered to be under clear sky conditions.

5.2.1. Variation Sequence

The 3D volumetric boundary condition is applied to the given site according to the information provided from procedure 1. Based on the steps to create the 3D boundary in procedure 2, the *Climatic Envelope* for Honolulu site is built as shown in Figure 5.2.

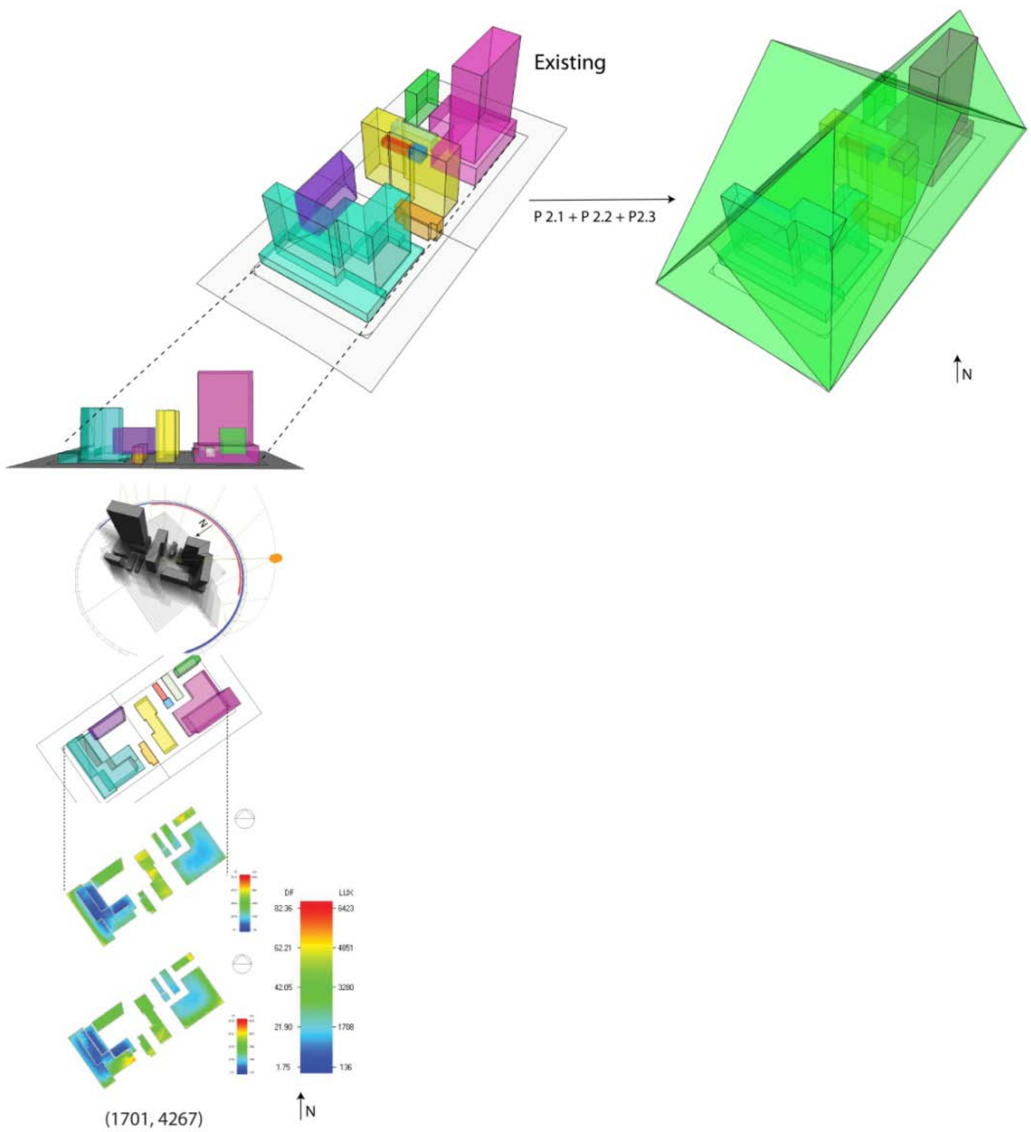


Figure 5.2. Honolulu Site: Shading analysis and Illuminance level map

[208] "Days of Sunshine."

Variation 1 is the result of the *Climatic Envelope* application and reconfiguring cut building blocks back into the corresponding buildings as shown in Figure 5.3. Because of the natural shape of *Climatic Envelope*, the buildings become angled after its application on the site. Tall buildings are mainly affected by the 3D boundary condition. In this case, they are the Pink, SkyB, Yellow, and a part of the Green building. Once cut volumes are reconfigured into a rectangular building volume, they are placed on the northwest side of the buildings based on procedure 5. According to P5.3, smaller building blocks are better to be placed in the northwest side under clear sky conditions. The illuminance level difference between the existing configuration and variation 1 under clear sky conditions is (416, 673). There has been 24% decrease of minimum illuminance level and 16% reduction of max illuminance. Although the illuminance levels under clear sky conditions are relatively high in the range of (1000, 3500), variation 1 shows that its configuration of buildings has produced an illuminance level that is closer to visual comfort level (300, 2000).

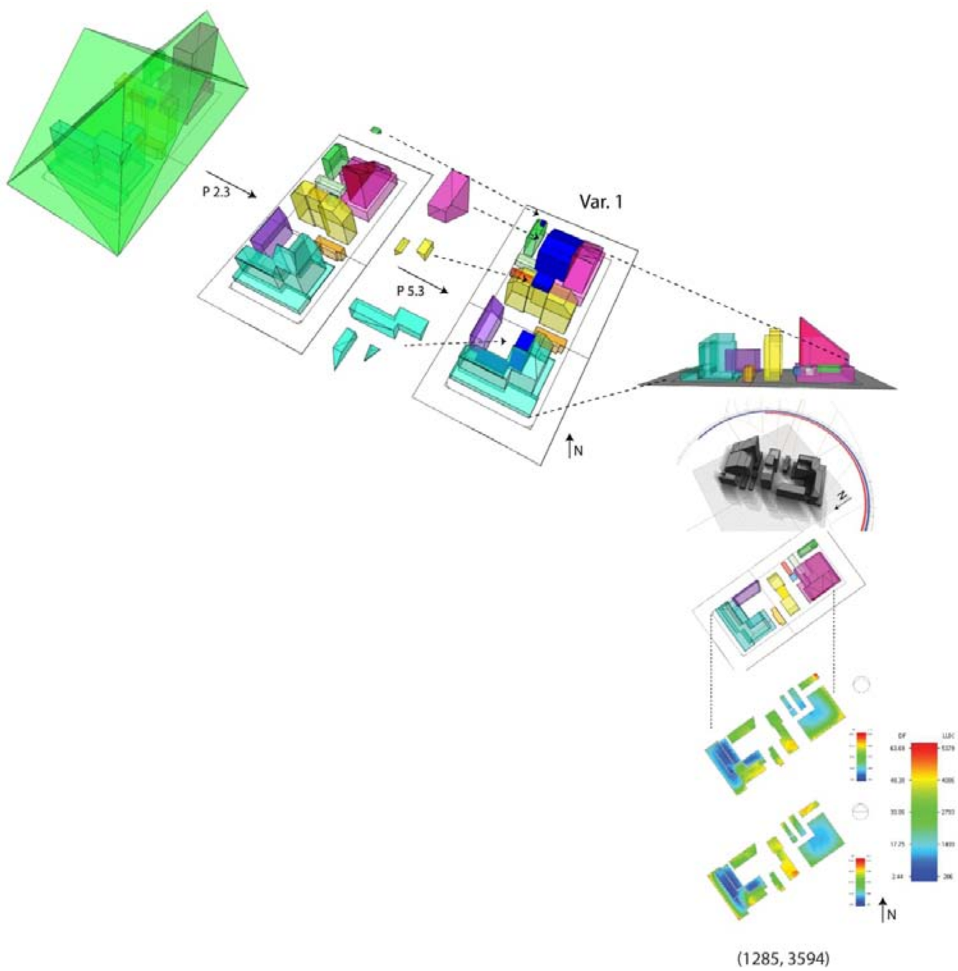


Figure 5.3. Variation 1: Climatic Envelope applied and Reconfigured Building Blocks

In variation 2, all the big volumes and tall buildings are relocated on the NE side of the site as shown in Figure 5.4. This is based on P 5.4 which guides that tall buildings are to be placed on the NE side of the site for a better visual comfort illuminance level. Based on P7.1, the sloped sides of tall buildings all face the SW side of the site so that southern exposure of buildings' wide surfaces is maximized. Since the application of *Climatic Envelope* automatically creates angled building forms, there is no need to regenerate buildings to angled forms under clear sky condition.

The illuminance level has increased from variation 1 to variation 2 by (195, 447). This indicates that the illuminance level increased by 11%. The difference is minimal so overall visual comfort would not be affected too much in this case.

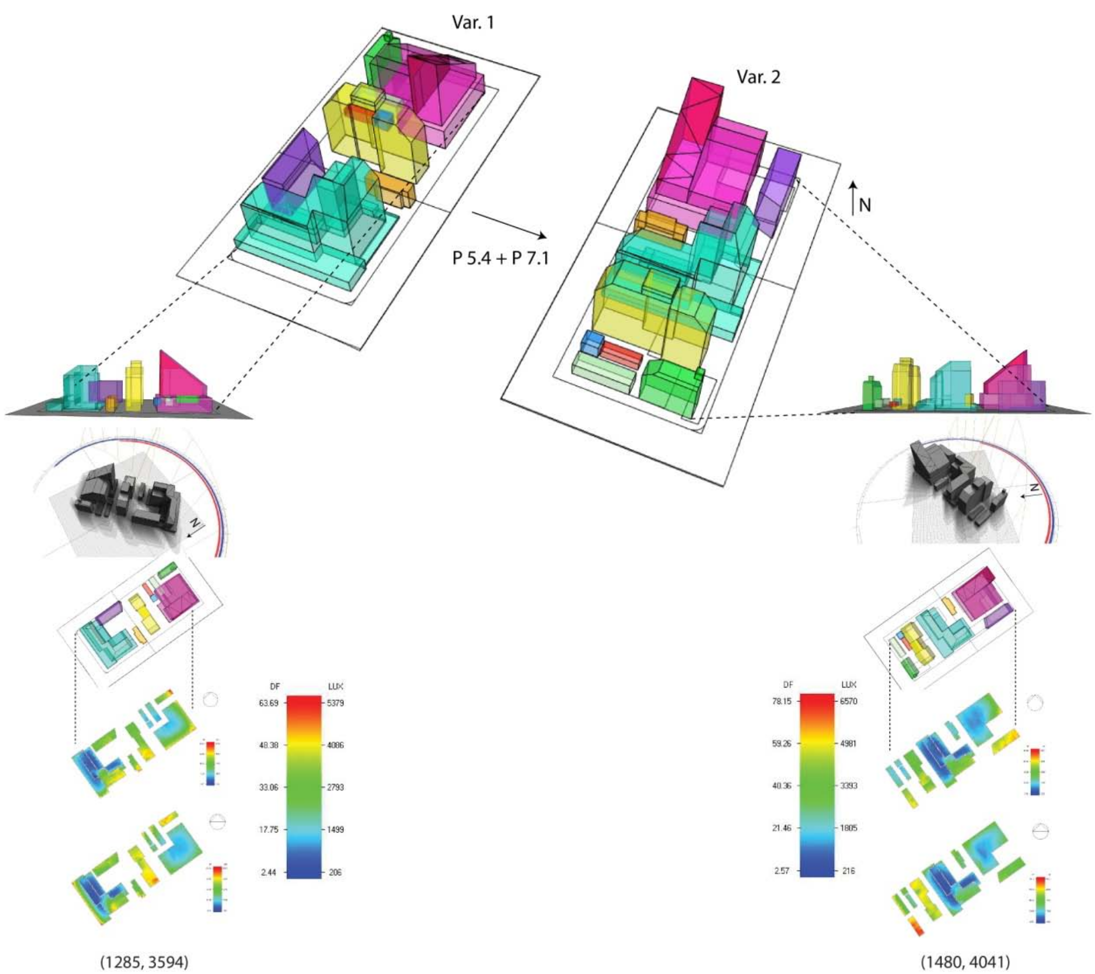


Figure 5.4. Variation 2: Relocating tall buildings in the NE side of the site

In variation 3, a 3D boundary condition has been applied to variation 2 as shown in Figure 5.5. The tall angles of the Pink building are drastically cut off in this case by the *Climatic Envelope*. Since the building volumes are minimized and redistributed back into the corresponding buildings, the average overall illuminance level of the buildings has become close to the illuminance level of visual comfort. The illuminance level difference between these two variations is (211, 530), so there has been 13% reduction of the illuminance level from variation 2 to 3.

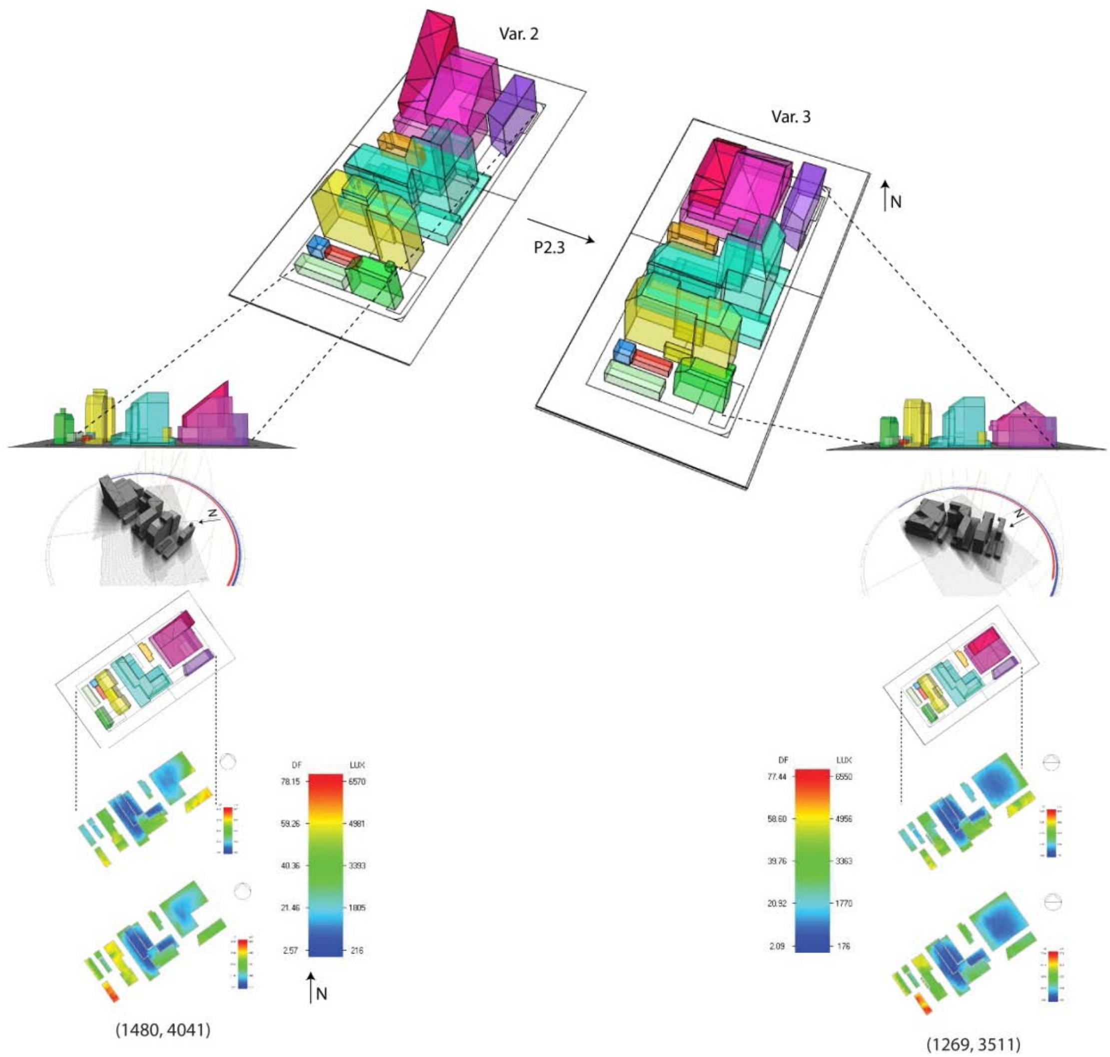


Figure 5.5. Variation 3: Applying *Climatic Envelope* on Var. 2

As shown in Figure 5.3 and 5.5, the application of *Climatic Envelope* and design rules for the configuration of buildings provide a reduction of the building's high illuminance level by transforming big building mass into smaller building sizes and modification of building forms. The application of procedure 6 has been embedded throughout the variation studies such that the distance between buildings have gotten shorter among buildings. In this way, a more compact building layout is created which led to a better visual comfort illuminance level.

5.1.2. Evaluation

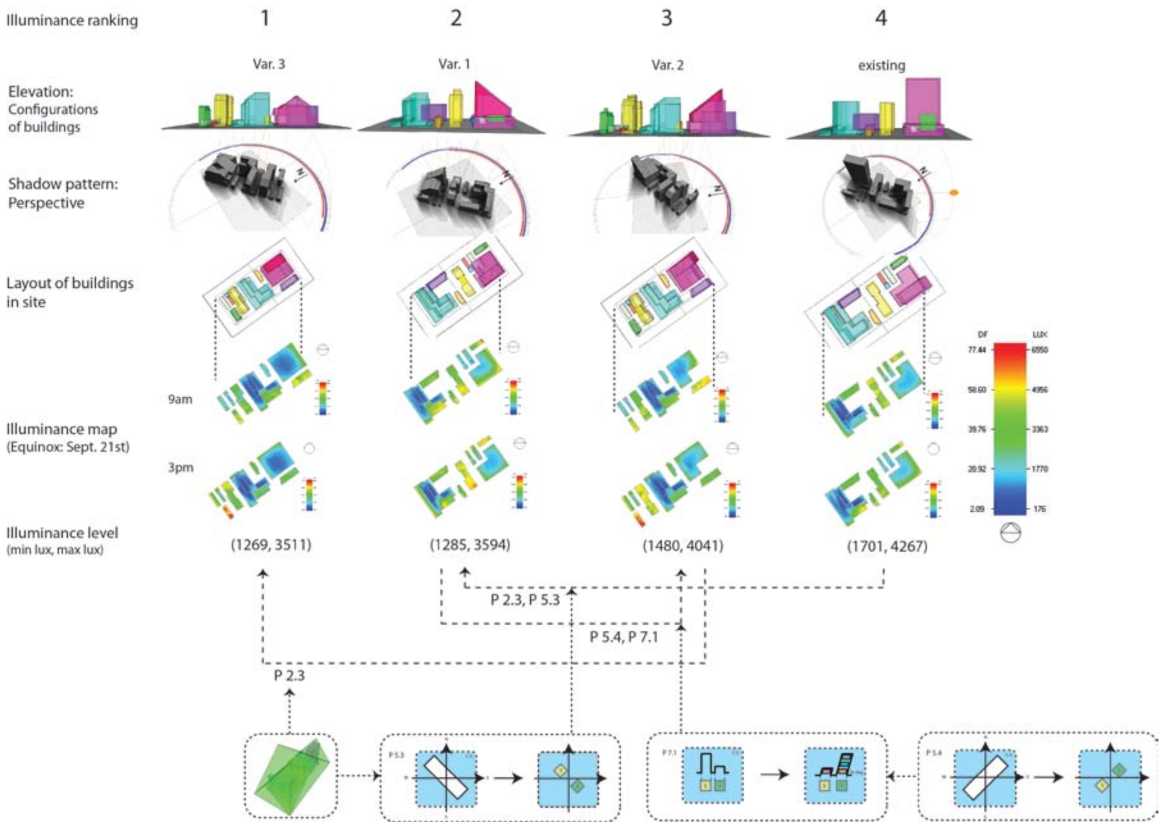


Figure 5.6. Illuminance Ranking and Summarization of Procedure Application: Clear Sky Condition, Honolulu, HI

Comparing the illuminance result between the existing configuration and the optimal configuration of buildings (Figure 5.6), there has been 25% for minimum illuminance level and 18% for maximum illuminance level. This confirms that the application of *Climatic Envelope* and criteria for configurations of buildings aid overall so that buildings can achieve an optimal visual comfort illuminance level. The overall layout of the buildings becomes more closed form than existing building when the illuminance level has gotten closer to the visual comfort level. Based on illuminance ranking results, placing tall buildings on the northeast side has not been as effective as placing smaller building blocks on the northwest side. Consequently, shorter buildings with multiple building blocks create better visual comfort illuminance level than tall buildings and big building masses.

Consequently, there are 5 confirmation points as the following:

1. Angled building forms lower the potential for glare more than straight-surfaced building forms. The following illuminance levels (min. lux, max. lux) are differences between straight-surfaced existing buildings.
2. Segmented buildings achieve better visual comfort illuminance level than one building with a large mass.
3. In clear sky conditions, compact configurations of buildings seem to work better to achieve visual comfort illuminance level because the buildings can shade to each other which lowers the potential for glare issues and direct sunlight.
4. Locating tall and bigger mass buildings on NE side is better than SW side.
5. Lower building heights can achieve the desired visual comfort illuminance level better than tall buildings.

5.2. Overcast Sky Condition

Seattle, WA has 301 days of sun out of a year, so 82% of the year in Seattle has clear sky.[209] The site in Seattle is considered to be under overcast sky conditions.The overall average illuminance level in overcast sky conditions is relatively lower than the illuminance level in clear sky conditions because an overcast sky only concerns skydome light which is diffused rather than direct. Reconfiguring the building shapes to stepped building form is one more step in the variation sequence under an overcast sky.

5.2.1. Variation Sequence

The variation study is started with the application of *Climatic Envelope* on the site as shown in Figure 5.7. A part of the Pink and SkyB buildings is cut off. The cut volumes are reconfigured as a simpler rectangular form and are placed back into the corresponding buildings based on P5.7. The illuminance level difference from existing site to variation 1 is (143, 124). The result is about 10 % reduction of the buildings' overall illuminance level which is very close to the illuminance level of visual comfort.

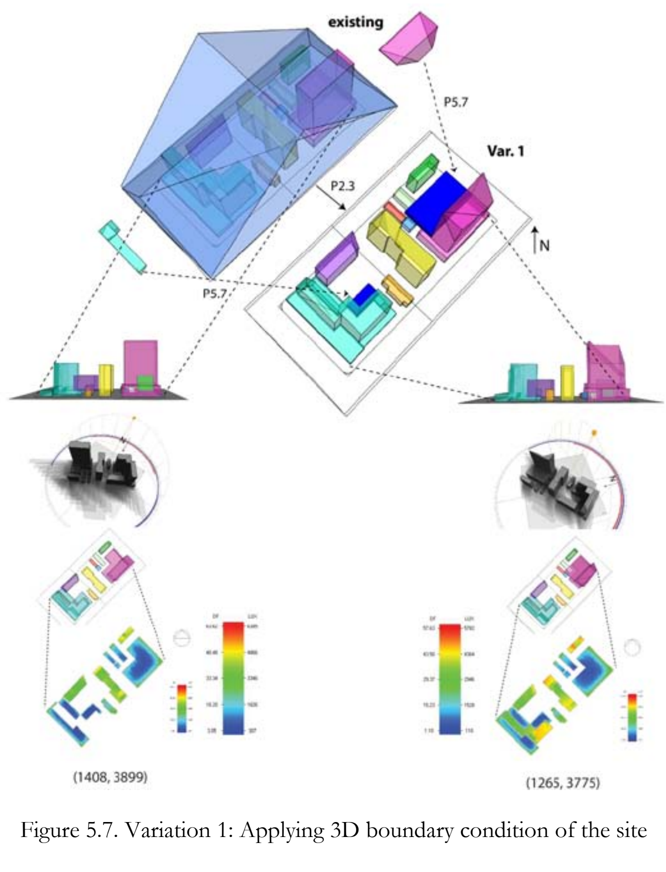


Figure 5.7. Variation 1: Applying 3D boundary condition of the site

[209] "Average Annual Sunshine in American Cities."

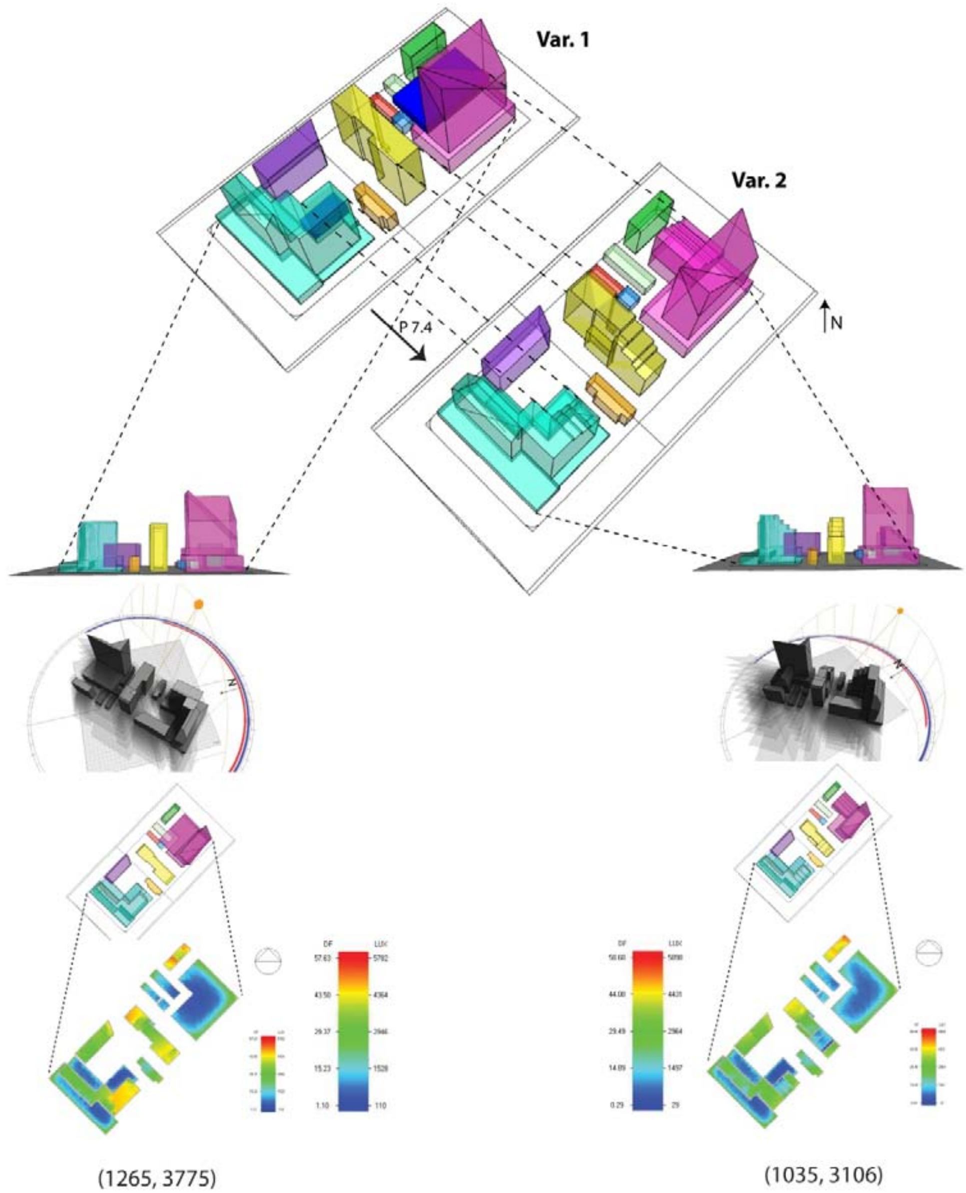


Figure 5.8. Variation 2: Transforming buildings into stepped form

Parts of the tall and large buildings are changed from straight form to a stepped form as shown in Figure 5.8. The stepped sides of each building different directions. For the Pink and SkyB buildings, the stepped sides face the northeast side while the Yellow building's stepped side faces the southeast of the site according to P7.4. The illuminance level of variation 2 is lowered from variation 1 by about 20%. This indicates that building form change has been an effective method for reaching a visual comfort illuminance level under overcast sky conditions.

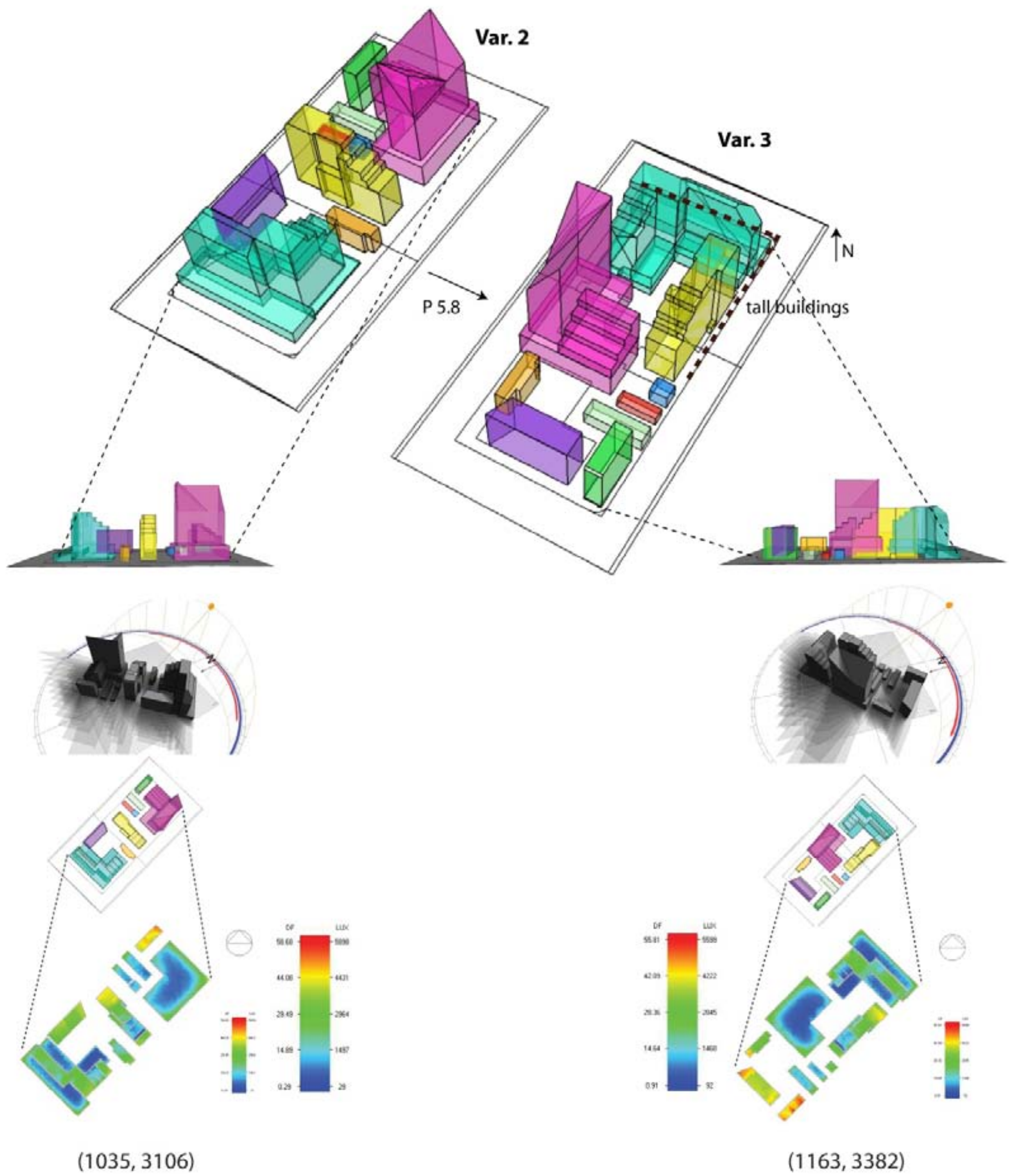


Figure 5.9. Variation 3: Relocating tall buildings to NE side

In variation 3, all the buildings are reconfigured to locate all tall buildings on the northeast side according to p5.8 as shown in Figure 5.9. The stepped sides of the three tall buildings; the Pink, SkyB and Yellow all face the southwest side in this case. As a result the overall illuminance level of this variation has increased by 11%. This is because the large surfaces of each building are exposed to the sun position. In this case, variation 3 has gotten closer to the visual comfort illuminance level under overcast sky conditions.

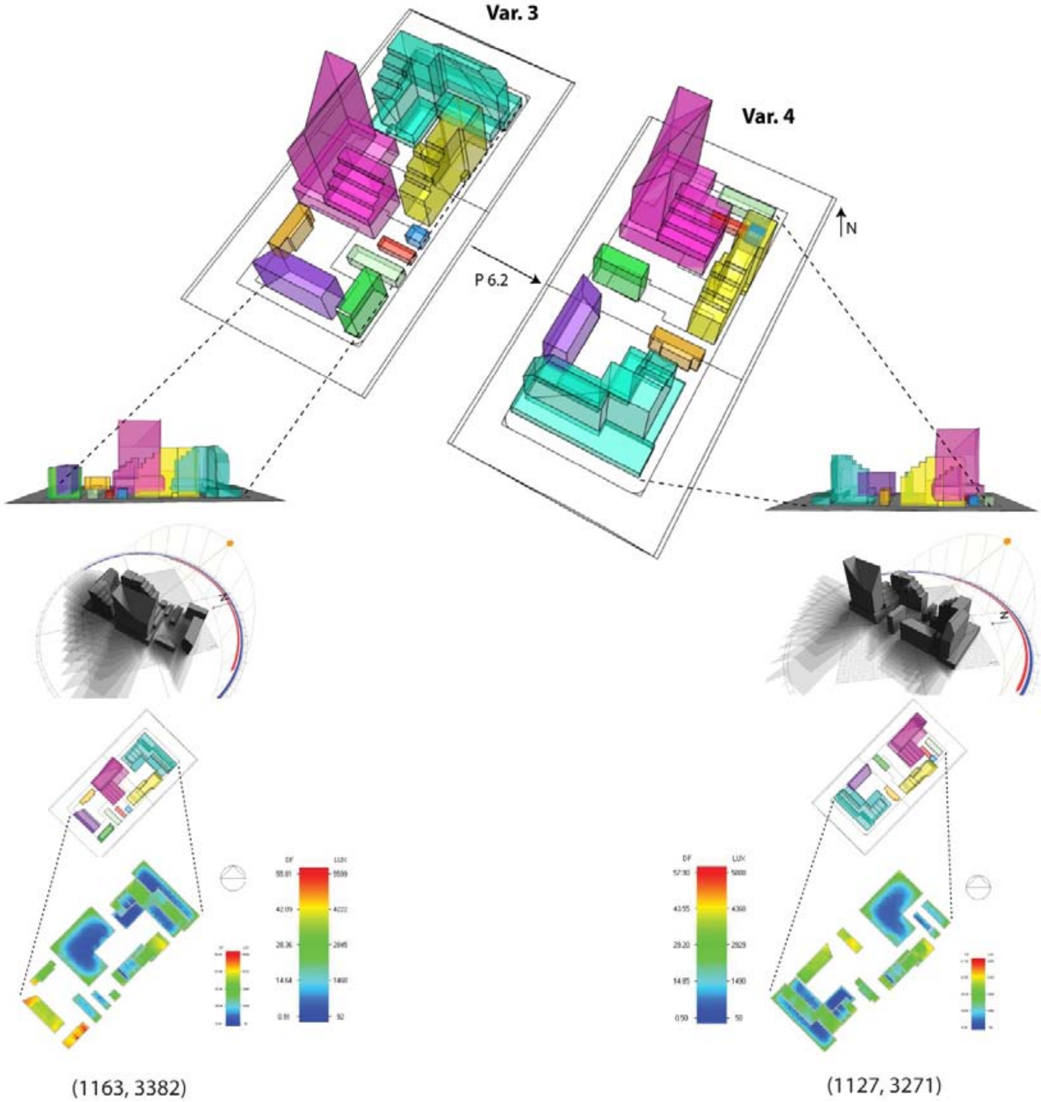


Figure 5.10. Variation 4: Spacing buildings

Since the buildings are clustered, the sun access is minimized in current variation 3. Therefore, the distance between the buildings is increased about 55% in variation 4 according to P6.2 as shown in Figure 5.10. In order to increase the building distances, the SkyB building has been relocated in the south western side, and its stepped side faces the northeast side. The illuminance level has been reduced by 3% which is minimal, but it is one step closer to visual comfort illuminance level and has created an opportunity for outdoor open space in the given site parcel.

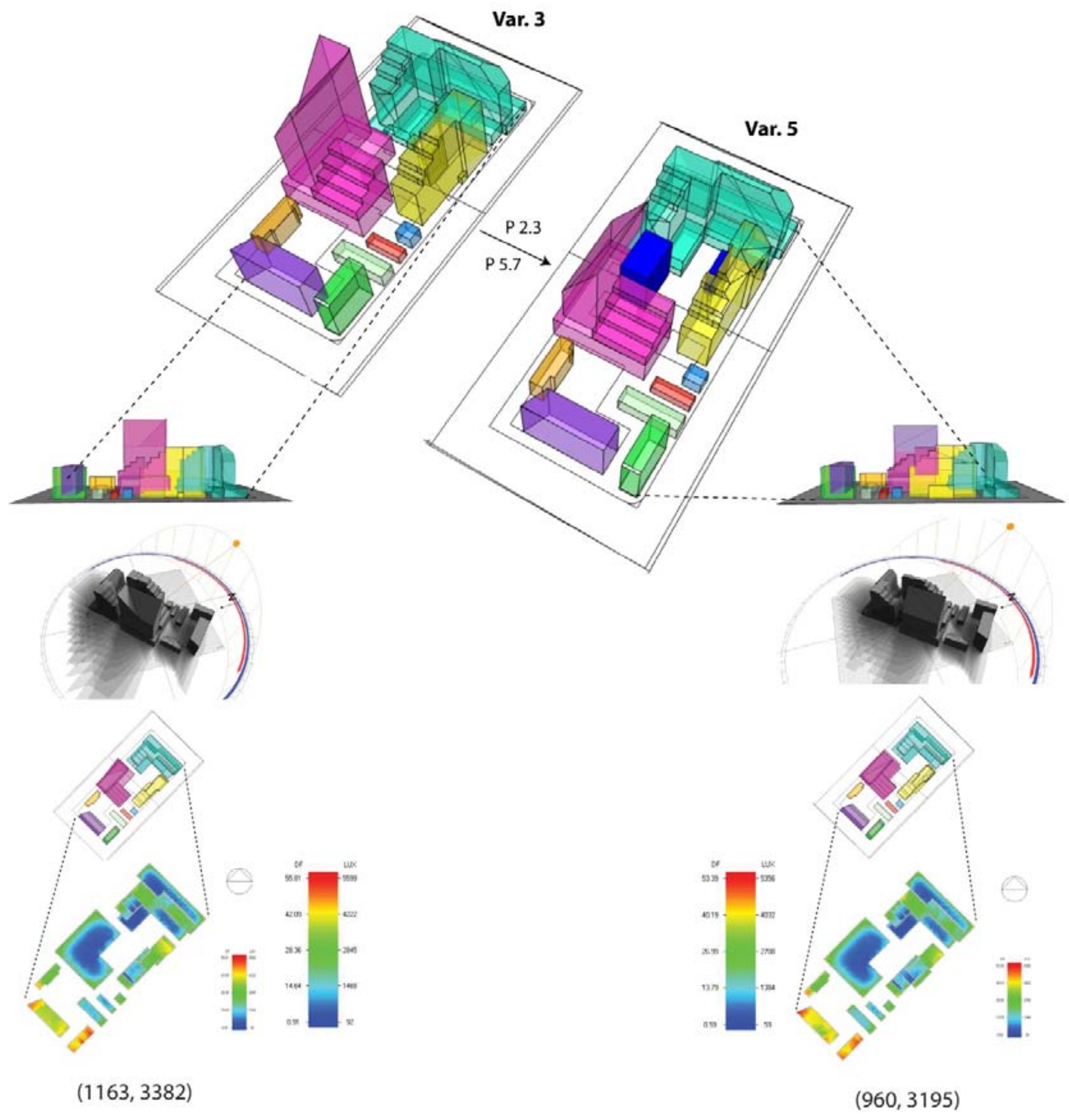


Figure 5.11. Variation 5: Applying Climatic Envelope to Var.3

According to P2.3, 3D boundary condition is applied to variation 3 which cut off more volume of the Pink and Yellow buildings as shown in Figure 5.11. The cut buildings are placed based on P2.3 which guides designers to move smaller cut volumes to the northwest side under overcast sky conditions. For the Pink building, there has been no practical space on the northwest side of the building so that the cut volume has been added on the northeast side of the building. The overall illuminance level of the configuration of buildings is reduced by 17%.

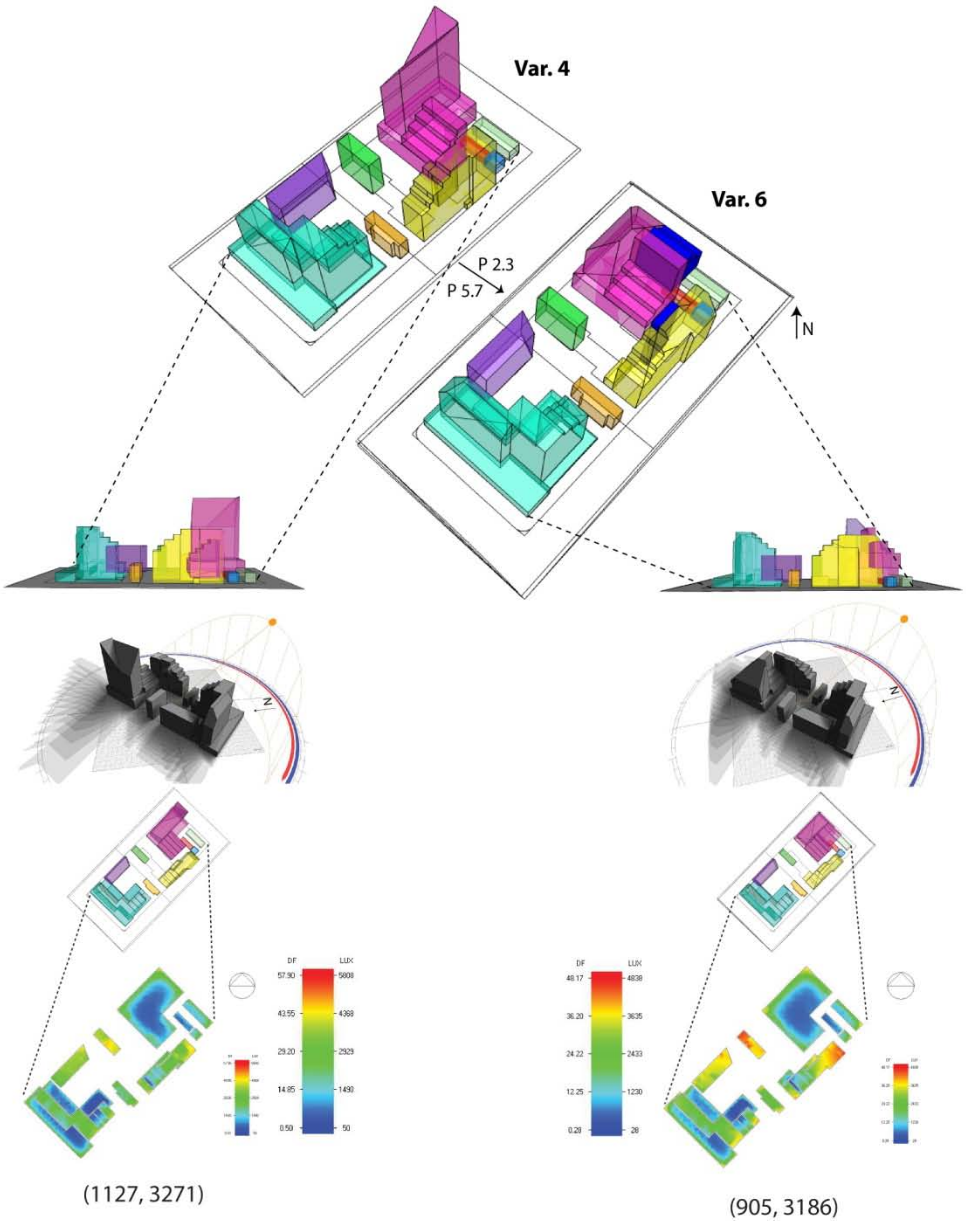


Figure 5.12. Variation 6: Applying Climatic Envelope to Var.4

When the 3D boundary condition is applied to variation 4, the volume of the Pink building is drastically cut down so that the height of the building has gotten shorter as shown in Figure 5.12. The cut volumes are put back into the corresponding buildings on the northeast side of the site based on P2.3. The illuminance level of variation 4 is decreased by 20% in this case. This illuminance level result(905, 3186) is the closest to the visual comfort level (300, 2000).

5.2.2. Evaluation

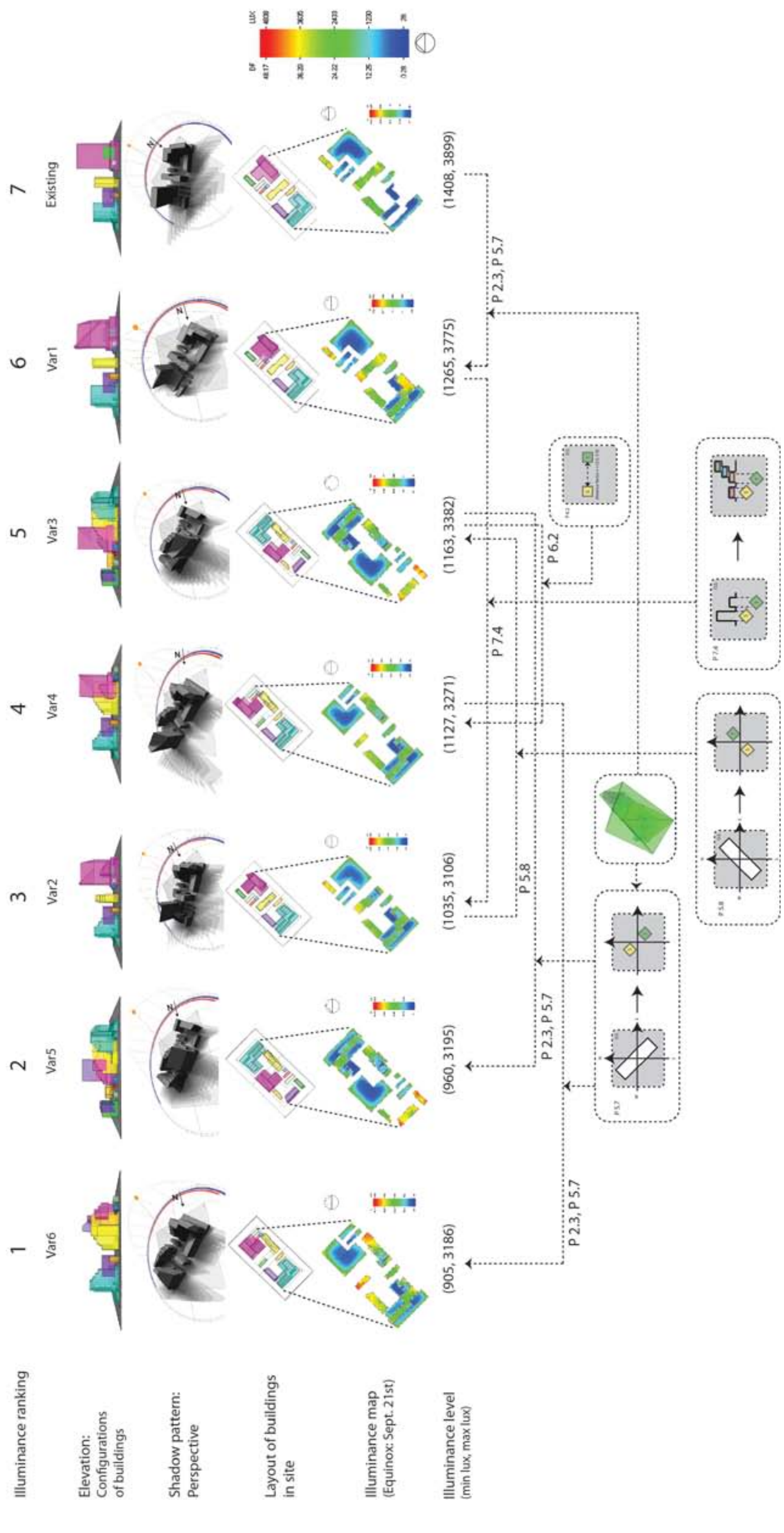


Figure 5.13. Illuminance Ranking: Overcast Sky Condition, Seattle, WA

As shown in Figure 5.13, comparing the illuminance results between the existing configuration and the optimal configuration of the buildings, the optimal configuration has obtained 36% improvement for minimum visual comfort illuminance level and 18% improvement for maximum visual comfort illuminance level. This confirms that the application of *Climatic Envelope* and design rules for configurations of buildings aid overall buildings to reach a level closer to the visual comfort illuminance level. The overall layout of the buildings becomes a more open form than the existing layout when the illuminance level has gotten closer to the visual comfort level. Reconfiguring building shapes to stepped building forms is one more step in the variation sequence under an overcast sky, and it creates various illuminance level differences depending on which direction the stepped sides face as shown in Figure 5.14.

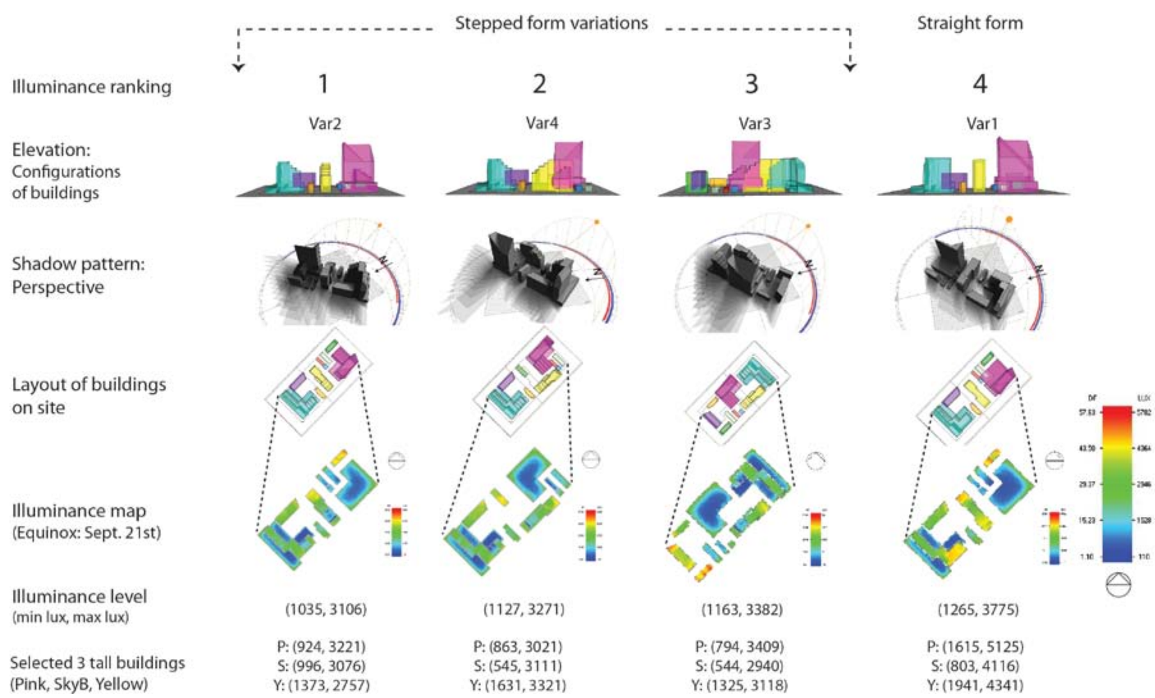


Figure 5.14. Comparing orientation and illuminance level of 3 selected tall buildings in stepped building forms and straight building form

3 different layouts of stepped buildings are compared to straight building forms from Climatic Envelope applied original configuration. Pink, SkyB and Yellow buildings are tall and large volume buildings on the site, and they have stepped building forms as a part of their building form. Changing the building forms into stepped forms has definitely decreased a high illuminance level overall. For the Pink building, illuminance level result has gotten better when the stepped building form faced the southwest side. For the SkyB building, the southwest facing stepped forms performed

better for the visual comfort. The Yellow building also has provided same result. Consequently, this confirms that stepped form on the southwest side provides optimal visual comfort in the non-cardinal NE-SW orientated site. This is because light comes in an angled manner and hits the horizontal surfaces indirectly, so that ambient light can reflected back into the space in the manner of diffused light. Climatic Envelope has not been applied to these three stepped building form variations yet, so there are slight difference in illuminance results. However, when the buildings are arranged in open layout, the illuminance level has gotten closer to visual comfort level overall.

Based on illuminance ranking results, placing tall buildings on the northeastern side has not been as effective as placing smaller building blocks on the northwestern side as shown in Figure 8. Consequently, shorter buildings with multiple building blocks create a better visual comfort illuminance level than the tall buildings and big building masses as well in this case.

Consequently, there are 5 confirmation points as follows:

1. Stepped building forms lowered the potential for glare by redirecting direct sunlight, compared to straight-surfaced existing buildings.
2. Segmented buildings achieve better visual comfort illuminance levels than one building with a large mass.
3. In overcast sky conditions, an open configuration of buildings seem to work better to achieve visual comfort illuminance level because the buildings can shade to each other which lowers the potential for glare issues and direct sunlight. Also, low building height is better than tall building height to achieve a good visual comfort illuminance range. The following shows the difference in illuminance levels.
4. Placing buildings in a dispersed way is better in this region. Stepped forms of buildings also face both the north and the south, so the sunlight exposure can be increased. Open layout means that tall buildings are usually located on the perimeter and small buildings are located inward or on perimeter to EW growth
5. Lower building heights can achieve the desired visual comfort illuminance level better than tall buildings.

5.3. Comparative Analysis

As shown in Figure 5.15, 64% of configurations of buildings in Seattle has reached the visual comfort illuminance range, and 43% of the configurations in Honolulu have gotten closer to visual comfort range. Because of direct sunlight access, it is inevitable for clear sky condition to have overall high illuminance level. This study only has looked at visual comfort illuminance level in the relation of multiple buildings regarding orientation, placement of buildings and building form, but in order to increase the overall percentage of visual comfort level, local shadings can be the most effective mitigating way to improve the performance.

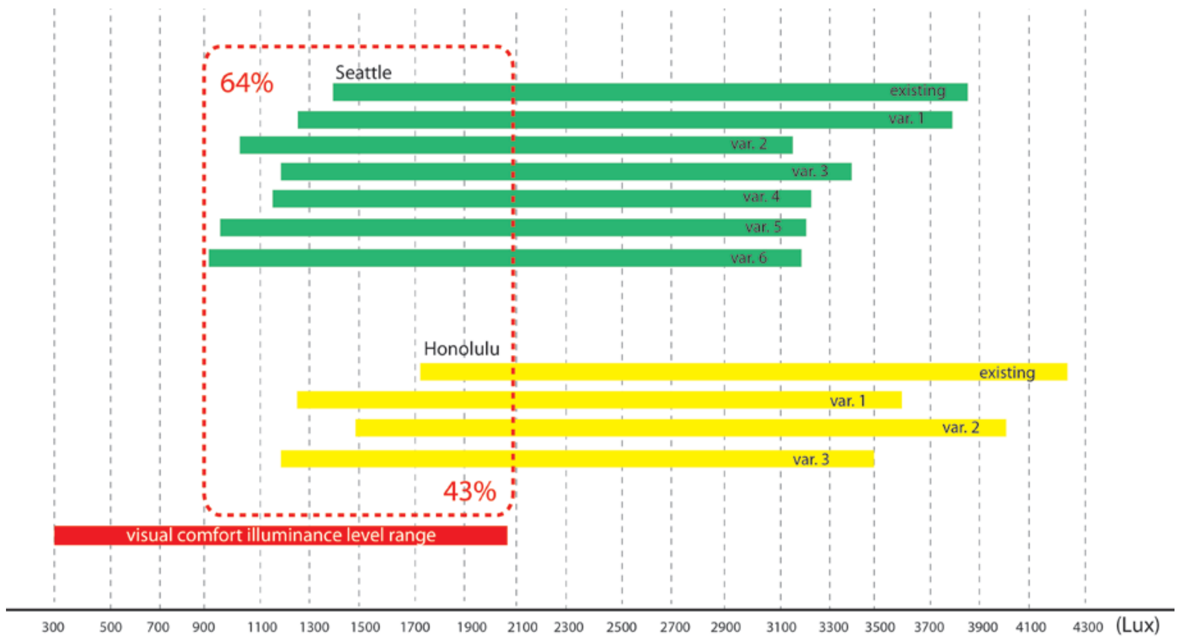


Figure 5.15. Comparing percentages of visual comfort illuminance level range between variations of Seattle and Honolulu

The number of variations in Honolulu is less than the number in Seattle because preferred building form has been generated automatically in the clear sky condition case when the *Climatic Envelope* is applied. The site itself has been relatively compact, so variation with distance between buildings has been limited.

In order to understand critical aspects that impact visual comfort under different sky conditions, optimal configuration of buildings from each site have been tested under switched sky conditions. The results identify short comings of the configuration in different sky conditions and ways to mitigate the identified issues.

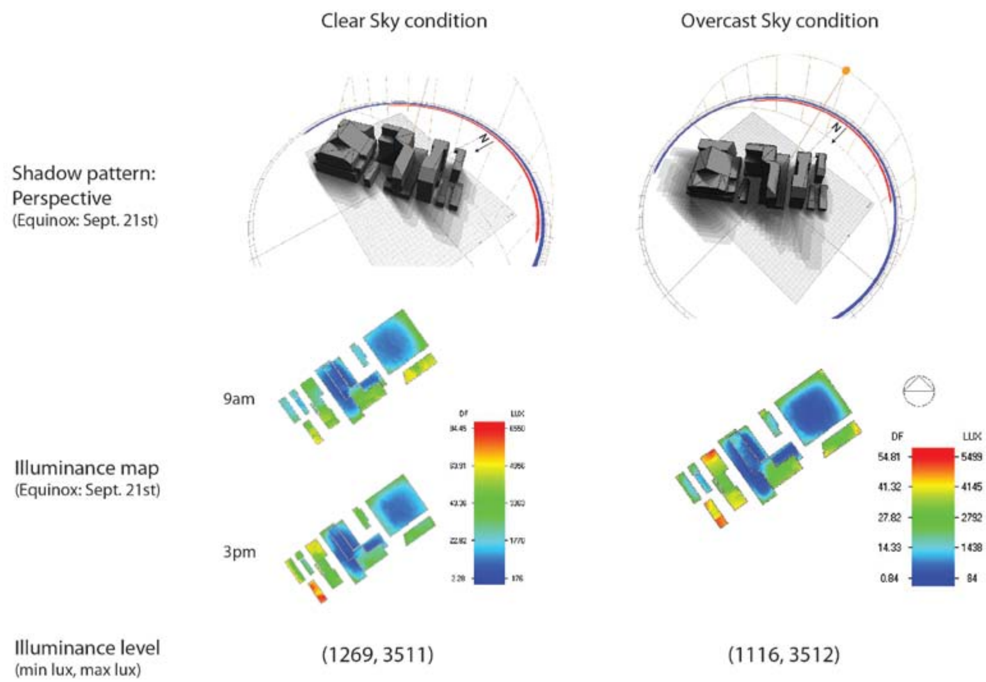


Figure 5.16. Comparison: Honolulu optimal configuration under Clear Sky vs. Overcast Sky Condition

When the optimal configuration of buildings from the Honolulu site has been simulated under overcast sky condition, the overall illuminance level has been reduced by 12% for minimum illuminance level but there has been no change on the maximum illuminance as shown in Figure 5.16. From the shadow pattern study of a model, many areas of the buildings are much shaded in the overcast sky condition because of the low degree of the sun path and close approximity of buildings, which was the reason of lower minimum illuminance levels. However, the overall illuminance level range is very similar to the results under the clear sky condition.

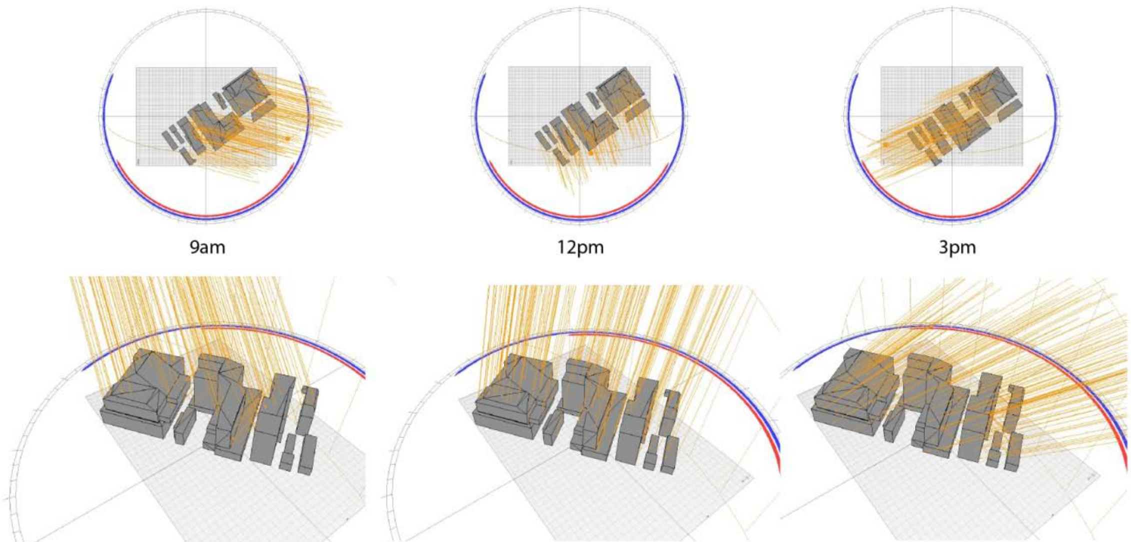


Figure 5.17. Sunray study: Honolulu optimal configuration under Clear Sky Condition

As shown in Figure 5.17, angled building forms work well under clear sky conditions to redirect direct sunlight, but because of high angle sun path, building form solely cannot mitigate the intensity of direct sunlight. In this configuration of buildings, compact layout of buildings definitely help to shade each other, and effective shading should be implemented to mitigate direct sun access. The Pink building especially has large exposed surfaces that should have a shading system that can control the sun access to the interior of a building.

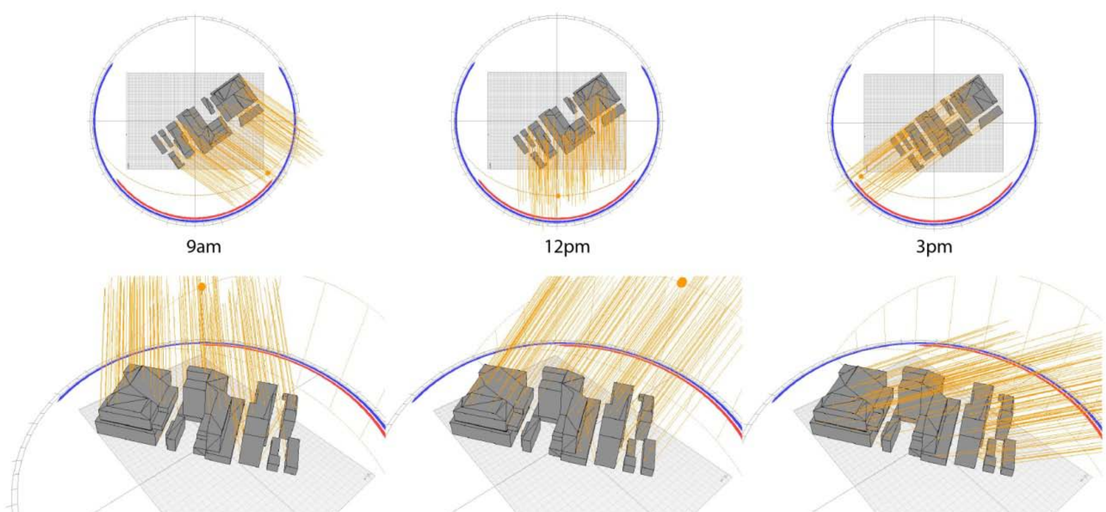


Figure 5.18. Sunray study: Honolulu optimal configuration under Overcast Sky Condition

Although direct sunlight is not an issue under an overcast sky condition, sunlight is still available through the clouds, as shown in Figure 5.18. Sometimes, overcast sky seems brighter than clear sky conditions because sunlight is diffused through the white clouds. Shading integration is also especially helpful for tall buildings. Integrating light shelves as shading and light redirecting surfaces would be useful to mitigate potential glare issues.

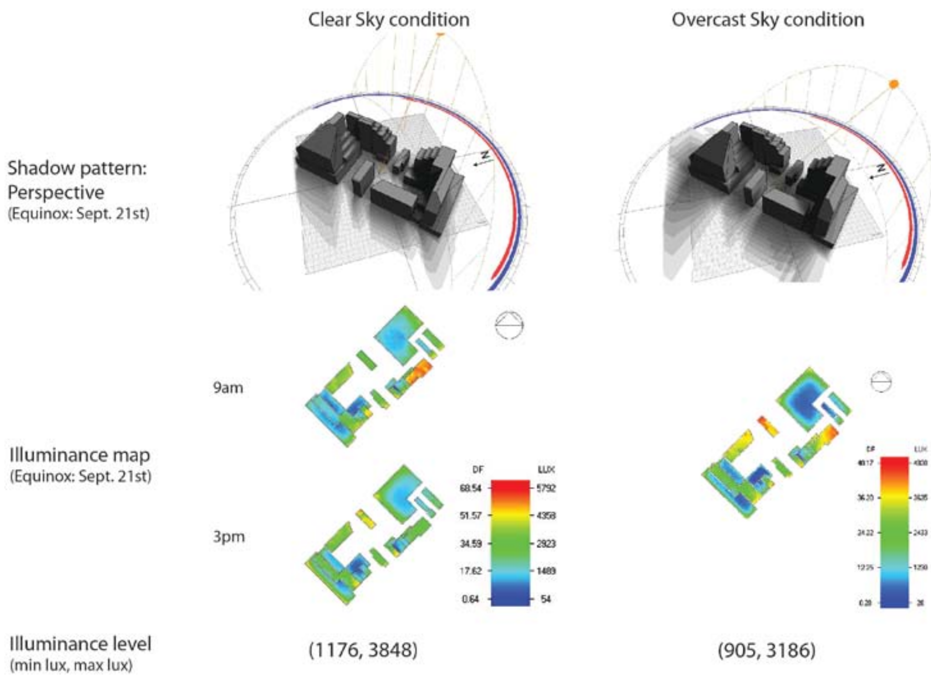


Figure 5.19. Comparison: Seattle optimal configuration under Clear Sky vs. Overcast Sky Condition

As shown in Figure 5.19, when the optimal configuration of buildings under overcast sky has been tested under clear sky conditions, the visual comfort illuminance level has increased 23% for minimum illuminance level, and 17% of illuminance has been reduced for maximum illuminance level. Since direct sunlight is abundant under a clear sky condition, it is expected to have higher illuminance level overall. However, an open plan layout would have increased excessive sunlight access to the buildings under this condition.

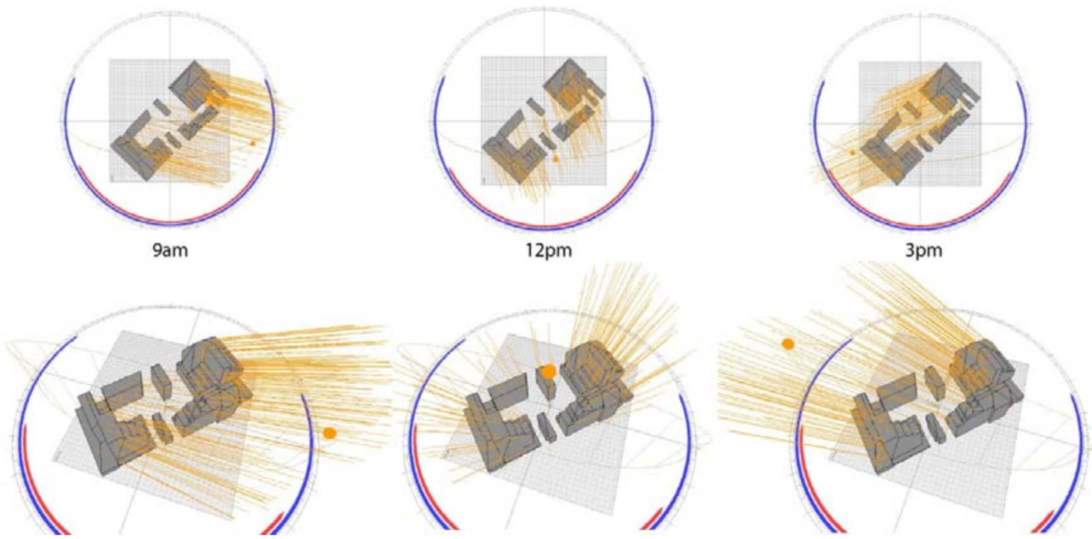


Figure 5.20. Sunray study: Seattle optimal configuration under Clear Sky Condition

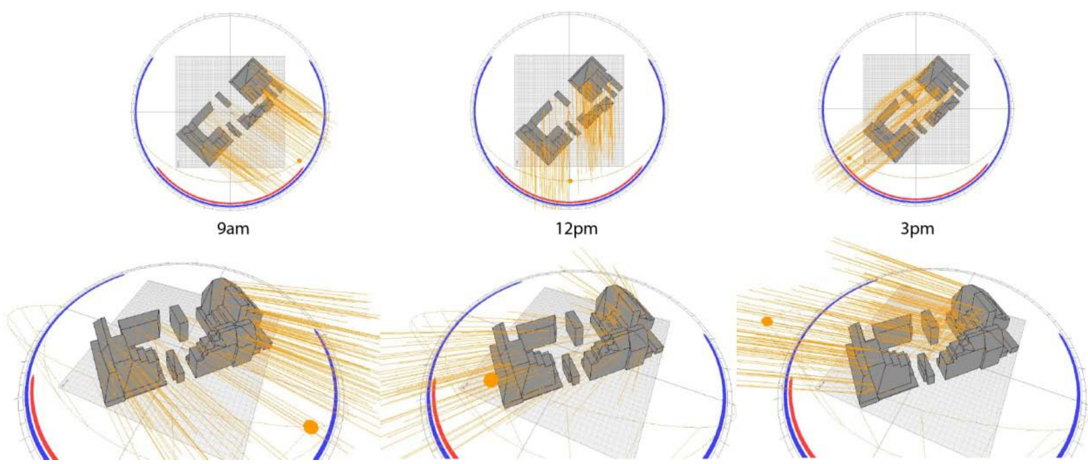


Figure 5.21. Sunray study: Seattle optimal configuration under Overcast Sky Condition

As shown in Figure 5.20 and 5.21, stepped building form is definitely effective for both clear sky and overcast sky conditions because the building form itself performs as a light shelf to redirect the sunlight. Ambient reflection from horizontal building surface can bring diffused light further into an interior. Especially for a clear sky condition, integration of local shading is necessary because the open plan does not have the same opportunity where buildings can be a shade to each other. It also may need exterior shading as well so that integration of outdoor and interior shadings can play off of each other to mitigate direct sunlight access to an interior. Local glare mitigation strategies such as placement of openings and window properties can be integrated based on sunlighting and daylighting strategies from chapter 2.

6. DISCUSSION

A daylighting synthesis-based integrated design procedure provides architects an opportunity to integrate daylighting as a design tool in the early design stage. The daylighting synthesis framework and procedure were developed to help and guide designers to create the configurations of buildings for optimal visual comfort at an urban-scape. The proposed approach included 1) the implementation of *Climatic Envelope* as a 3D volumetric boundary of buildings in a given site and 2) design rules for configuration of buildings under clear and overcast sky conditions of the site.

The significant contribution of this study lies in the development of design rules for configurations of buildings. There have been many daylighting strategies and principles developed for buildings on an individual basis. However, there has not much been done in developing a strategy and rule set for daylighting design on multiple buildings. The design rules allow architects to integrate daylighting into the relationship of multiple buildings with the goal of visual comfort. The daylighting design components applied in the development of these design rules are not new, but they are systematically redefined with the intent of configuring buildings for the optimization of visual comfort.

This investigation also broadens the designer's perspective on integrating environmental factors as a design tool in the architectural design process. Environmental factors are usually perceived as an analysis tool to evaluate building performance in regards to human comfort. They are understood more as technical tools. Therefore, these factors are often considered after the architectural design is near completion. This integrated daylighting design framework and procedures open up the possibility of implementing environmental factors in the early design stage so that they can be an integral part of designing the holistic picture of building relations. This research is significant in architecture discipline that it introduces to examine human comfort beyond a single building, but in the relationship of buildings in an urban scale.

One future study of this research is the investigation of how this framework and procedure impact space planning, energy savings, architectural programming or human functionality. The integration of daylighting in a single building alone has been proved to have various benefits in human health, productivity and energy savings. It is necessary to further examine whether this framework and procedure can provide the same benefits or more beyond visual comfort if daylighting is integrated in the relationship of multiple buildings. Another future study includes the application of parametric modeling based upon design rules to generate various configurations of buildings. Designers may benefit from fast visualization of configuration options which will save design process time in the architectural design.

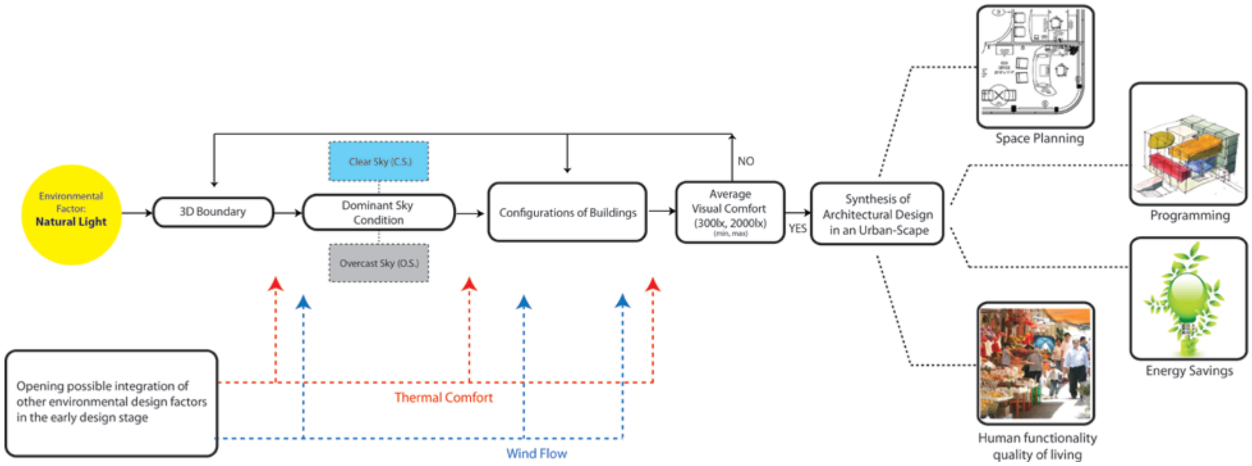


Figure 6.1. Future studies of synthesis-based integrated daylighting design framework

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