INTELLIGENT BUILDING SKINS:

PARAMETRIC-BASED ALGORITHM FOR KINETIC FACADES DESIGN AND DAYLIGHTING PERFORMANCE INTEGRATION

by

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ABSTRACT

A high integration of design and research between architects, computational designers, and consultants is important to achieve innovation and efficiency. Communicating to the designer the importance of integrating performance-based approaches in the early design stage and their impact on the design, may shift the logic of executing an architectural project. The integration of daylighting into the design phase, through design tools and computation, results in the improved performance of daylight harvesting and therefore tackles issues of human comfort and energy efficiency. One example of performance-based integration is the design, simulation, and validation of intelligent features in building skin design and its impact on daylighting performance.

This thesis presents the design of an algorithm and parametric process developed in Grasshopper, a plugin for Rhino 3D, using DIVA for daylighting simulation. The main objective of the process and algorithm is to evaluate the performance of an intelligent façade, composed of a series of kinetic louvers that actuate in response to dynamic daylighting, and the incorporation of occupants' preferences. Within the framework of this study, Grasshopper as a parametric computational tool allows the integration of Rhino, the design space, and DIVA, the dynamic daylighting tool, into a single process. The parametric tool extracts the designed geometry from the modeling space and inputs it into the DIVA component to be tested for illumination performance, luminous distribution, and daylight penetration depth inside an office space.

The thesis presents the initial experiment, in which the external skin actuates to optimize daylight-deflection, maintaining a desirable luminous indoor environment. In the experiment, the louvers rotate using the concept of independent tilt-angle, where every other louver has the same tilt angle; they could be in a harvesting, shading, or a combined configuration. When skin configuration changes, due to louver actuation, the algorithm detects the alteration and instantly reflects it onto a calculation grid inside the space. This allows the designer to run numerous iterations during the design stage and select the best possible one based on pre-defined criteria.

A genetic algorithm has been incorporated into the definition to enable a search for the best skin configuration at specific dates and times or under different sky conditions. The genetic algorithm works on finding an optimal – although not necessarily the best – solution under certain parameters and conditions. These parameters could range from users' desired illumination levels, to externally-reflected daylighting components. Changes in any of these parameters trigger the system to run and find an optimal configuration for the skin to maintain the desired luminous environment.

In this study, one actuation parameter and three performance indicators for daylighting are defined. However, the proposed design tool is extensible; it is open to accepting additional parameters and performance indicators, which makes it more complex for better performance assessment. As a future development, the geometry of the skin panels will be considered as a varying parameter.

1. CHAPTER 1 INTRODUCTION

This research presents an investigation into using intelligent light-deflection techniques to optimize daylighting in office buildings. In this chapter, the background of the proposed topic, the research argument, and the objectives of the study are presented, along with insight into the methodology and intended deliverable

1.1. BACKGROUND

Figure 1-1: Curtain Walls – The left image shows one of the world's first curtain walls in England, Oriel Chambers. The right image shows a building by the same architect, which also has a curtain wall system, built two years later. At this time, the amount of glazing used was large compared to adjacent buildings in the area. The architect's goal was to allow more daylight penetration into the space, as a means of energy-saving.[1]

In 1864, Peter Ellis designed Oriel Chambers in Liverpool[2], England, one of the world's earliest buildings with metal-framed glass curtain walls. Peter was considered a substantial user of glass facades. His design intent was not aesthetic, but had more of an emphasis on energy efficiency.

[1] "Curtain wall - Wikipedia, the free encyclopedia."

[2] "Liverpool Architecture."

The penetration of daylighting deeply into the space, reducing lighting costs, was the main objective for using curtain wall systems. As time passed, architects started incorporating more glass into their facades, resulting in high levels of illumination inside the spaces. The use of larger amounts of glazing became more common, which made architects worried about their façade performance, and they started looking at the façade as an important filtering layer to the indoor environment.

In the United States, lighting accounts for almost 20-25%[3] of total electrical energy use, and in the commercial sector accounts for 37%[4] (Figure 1-2). Electric lighting also has an indirect effect on cooling loads in spaces; as a rule of thumb, each unit of electric light requires an additional one-half unit of electricity for space conditioning.[5] Improvements in the lighting design profession increased the efficiency of lighting, by utilizing less electrical lighting and exploiting the available natural light. The impact of using natural light is significant not only in terms of energy usage, but also on employees' productivity and health[6].

Use of daylight is important not only in offices, but also in most architectural projects, including retail spaces[7]. In a comparative study by Southern California Edison of a large multinational

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[3] Ander, *Daylighting Performance and Design*, 2.

[4] Ibid.

[5] Ibid.

[6] Dasgupta, *The Impact of Windows on Mood and Performance of Judgmental Tasks*.

[7] Ander, *Daylighting Performance and Design*, 31.

retail organization, an approximate 26%[8] increase in sales has been noticed in a store with skylights, relative to similar stores with no skylights.

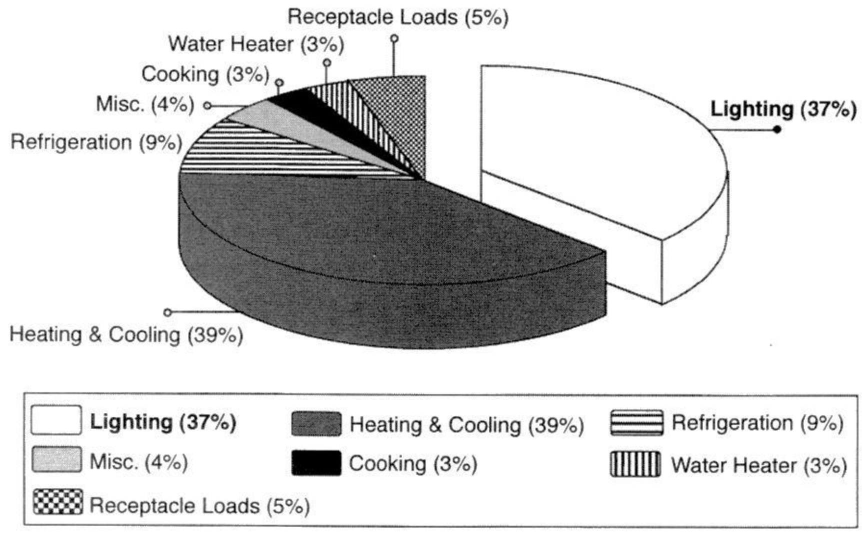

Figure 1-2: Electricity Use in USA – breakdown of electricity consumption in the commercial building sector.[9]

The use of glass in office buildings has become important in the profession for transparency, visual, and daylighting purposes. Although useful for allowing light into buildings, untreated windows allow more daylight into a space than required, resulting in visual problems, such as over-abundance of light in some areas, not enough in others, and glare. Typically, the daylight depth in a room with untreated openings is about one-and-a-half times the distance from the window head to the floor (Figure 1-3). A typical window head is at 2.20m, which results in a 3.30m room depth of daylight area. Using light deflection techniques, such as light shelves, can

[8] Ibid.

[9] Ibid., 2.

extend the ratio up to twice that height, resulting in a daylit zone of 4.40m depth.[10] This ratio shows the limitation of daylight penetration, which entails the use of electric lighting in many indoor spaces, leading to greater electrical energy consumption, and greater heat from light fixtures, in addition to that from sunlight. This is still a major balancing act in window design: daylight harvesting can help save energy through reduced use of electricity to run lights, but the heat gain might be undesired. As mentioned previously, light shelves are a good solution for deep light penetration up to twice the window header height[11]. The principle behind this idea is light-deflection, in which light is bounced off the upper surface of a shelf and deflected deeply into the back of the space. This technology opened new venues for the advancement of daylighting performance inside spaces, especially in office buildings. Amongst the technologies that allow better daylighting efficiency, redirecting light either into or out of a space is commonly referred to as *light-deflection technology*[12].

[10] O'Connor, *Tips for daylighting with windows: the integrated approach*, 3.

[11] Ibid.

[12] "Thiele AG - Transparente Innovation."

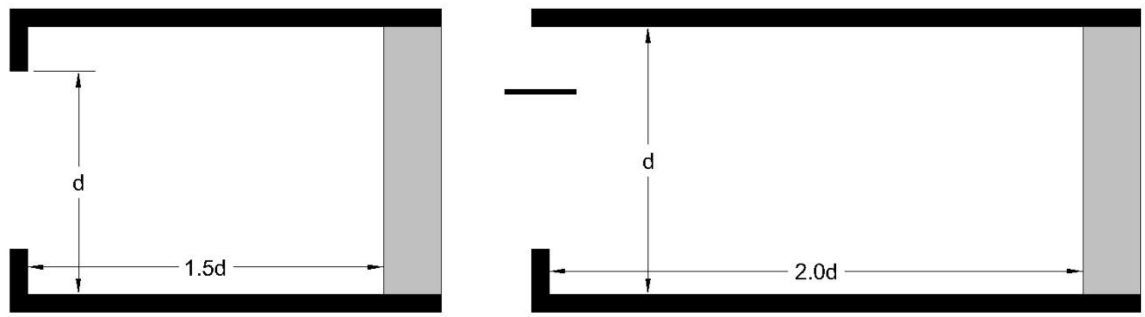

Figure 1-3: Daylit Zone – the figure on the left shows the depth of daylight in the case of an untreated window opening, while the right figure shows the depth extended up to 2.0x using light shelves.

The introduction of light redirection technology had a significant impact on the performance of facades in optimizing daylighting[13]. Light deflection devices have been proven to efficiently increase the performance of daylighting in interior spaces, by redirecting light deep into the spaces, minimizing the undesirable effects of direct sunlight and the use of electric lighting. Such systems include light shelves, light tubes, venetian blinds, and anidolic systems. While these techniques have the same objective - increasing the amount of daylight in interior spaces - they are not suitable for every building. For example, using light tubes in a high-rise office building is not an efficient approach, given the typical height of a high-rise tower.

Daylight problems are mostly treated as individual cases, in which system customization is sometimes required. Such customization does not have to involve the major alteration of an existing technology, but can be a minor addition that makes the system fit within the design

[13] Koster, *Dynamic Daylighting Architecture*.

context. The system can be a passive daylight system that aims for better lighting inside spaces, or a static or active system that possesses some dynamic capabilities. While passive systems enhance performance, they lack the flexibility of adapting to changing outdoor conditions. For example, fixed light shelves are optimized for specific ranges of dates and times, and are less effective for the rest of the year or under different sky conditions. The ineffectiveness of light shelves is due to the changing angle of the sun. Given the limitations of passive systems, designers started adopting active control systems, which led to the introduction of kinetics techniques in façade design.

Over the past few decades, architects have adopted kinetic systems in many glass façade systems, for their interactive abilities - and not particularly for environmental purposes[14]. Having movable devices on a building façade was a turning point in the profession. However, a façade can be referred to as "interactive" without possessing kinetic capabilities. Media facades are one type of interactive architecture, considered socially interactive due to their use of lights. They are even sometimes considered to be sustainable, when they use solar energy as a renewable energy source. Other types of interactive designs include wall prototypes designed by some architects for social interaction purposes, in which a wall is able to respond to an occupant's motion. But these are also irrelevant to our current environmental needs, since they only address artistic and aesthetic issues.

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[14] "FLARE-facade."

Figure 1-4: Flare Façade – The modular façade is composed of metal flake elements that are controlled by a series of pneumatic cylinders. These elements reflect sunlight in a way that casts a shadow on some of the faces of each element, giving them darker colors. The façade does not optimize the energy performance of the indoor spaces, but socially interacts with people outside the building and operates as an interactive piece of art.15

Architecture is currently experiencing a demand for smart, responsive-based designs, where the occupants' comfort level is achieved through means of perception, processing, and response. Buildings are becoming more like high performance working robots/machines. Designers are investigating the potential of making façade elements move in response to other stimuli, whether human or natural. If we are to develop the field of architecture and performance-based design, the profession needs to restructure traditional kinetic approaches to make use of

[15] Ibid.

today's technology, beyond conventional mechanisms and single-function design. Venetian blind systems that are programmed to retract and close at certain times of the days are an example of conventional kinetic techniques.

> It is worth noting that a number of studies have demonstrated that the ability of an employee to control to a degree the daylight and electric light directly around his or her work area has led to even better production and morale. This is because, while overall good lighting is important, individuals often have their own particular preferences for brightness and the angle from which light hits their work area.[16]

The statement above proclaims the need for individual control of daylight and electric light around an employee's working area. Given today's technological advancement, individual control can be provided in the form of an automated-smart system: a system which stores the preferences of the occupants and acts accordingly to adjust the quality of the luminous environment inside the space, without the need for manual human control.

Integrating intelligent features into the architecture of a building is a discourse taking place in the architecture profession. Façades that possess intelligent capabilities are always referred to as "Intelligent Skins". In Chapter 2, the research presents a detailed explanation of intelligent skins. Intelligent skins touch upon not only energy performance, but also the aesthetics of the design. This combination is the focus of many interactive architecture designers, such as Michael A. Fox and Chuck Hoberman, who try to use intelligence to transform façade panels whenever needed in response to natural forces. The design of façades, an important element of architecture, is influenced by changes in design trends, in terms of geometry and systems.

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[16] Ander, *Daylighting Performance and Design*, 28.

Many designers, some of whom are famous, are incorporating greater geometric complexity into their designs. This approach to design has become more widely used for landmark and iconic architecture. While complexity is also found in systems and structure, this aspect addresses complexity in terms of form and geometry only. Designing a building with complex geometry does not obviate the need to perform better in terms of energy-efficiency. An optimal approach in this case is to combine arts and science to support whatever design path the designer is undertaking, by providing advanced technological solutions. Though complex geometry is not in the scope of this thesis, it could be approached using the same technique as a regular façade: one way of integrating advanced technology is through the use of dynamic techniques and capabilities.

Dynamic kinetics is a façade typology that integrates movable panels into one large system, the *envelope*; it is an integral part of the whole building, acting independently. Within the scope of this study, dynamic capabilities are applied to a secondary skin, where the building has two external facades: one has the glazing, and the other is offset from the glazing by 1.00m and consists of a series of horizontal louvers. The offset distance allows for accessibility and maintenance activities to take place. While in this study the secondary skin is a series of kinetic horizontal louvers, it can be found in different forms and configurations based on the project's objectives, whether performance-based or aesthetic.

In this case, the horizontal louvers function as light-deflection devices capable of adapting to environmental changes. The use of light deflectors as a secondary skin on a building requires proper rationalization of the system to match the desired geometry of the architecture. This sometimes requires system customization using commonly-used technologies, developing a new approach using established techniques. If we are to make a significant contribution to the field, we have to commit to a new paradigm based on innovative development of the old.

> Signal your intention. Commit to a new paradigm, rather than to an incremental improvement of the old…. In this case, the intention is not to be slightly more efficient, to improve on the old model, but to change the framework itself.[17]

This statement by McDonogh and Braungart is inspiring for designers to look forward and support today's technology in the design profession. It reflects the need for an innovative framework that adapts to current performance needs, rather than altering old techniques and making them fit within a new context. Good practice should experience a fluidity of design and scientific creativity flowing between architects and consultants, in order to achieve innovative buildings. Rethinking the design program may be better than refining an old approach to fit the target problem - the designer should make use of existing techniques and approaches to develop a new, perhaps customized, technique for solving design and performance problems. It is crucial for the development of our profession that designers learn from the past, explore the current, and innovate for our changing environment and demands.

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[17] McDonough and Braungart, *Cradle to Cradle*, 182.

1.2. RESEARCH STATEMENT

Energy efficiency in buildings is influenced by the behavior of architectural spaces, part of which can be attributed to daylighting. Daylighting performance is envelope-dominated. For example, designing fully-glazed façades minimizes the efficiency of the envelope, despite allowing huge amounts of daylight into a space. This does not necessarily result in good performance, since illumination levels are not optimized to fall within the acceptable range. The problem is notably experienced in south facing façades, which get the most solar exposure over the course of the day.

Daylighting is a crucial asset for office design, but it is variable. Indoor spaces suffering inadequate daylighting levels during daytime experience illumination levels (quantity) out of the recommended range, and uneven distribution of daylighting (quality). They also suffer the need for electric lighting to compensate for the limitation of daylighting depth into the space. The design profession is currently undergoing technological advancement which will allow for better daylight performance, targeting greater energy savings and reduced electricity consumption. This will happen by bringing daylight deeper into the space, maintaining desired illumination levels (quantity), and achieving even luminous distribution (quality).

The integration of light deflection techniques into an intelligent dynamic panel system allows the enhancement of daylight harvesting, quantity and quality, inside south-facing spaces enclosed by fully-glazed façades – *Hypothesis*

This hypothesis combines two different aspects of architecture that correlate: “intelligent skins” and “daylight-deflection technology.” Within the context of this thesis, 1) intelligent skin is the means through which 2) daylight-deflection is enhanced.

The statement focuses on the intelligent dynamic panel system and its impact on the quality and quantity of daylighting in office spaces. Investigating this topic requires defining particular specifications, among which are daylighting benchmarks and the qualities that distinguish an intelligent envelope performance. In Chapter 3, an explanation of the qualities and specifications of daylighting in office spaces is presented. These qualities vary, and include such factors as sensors and controls, patterns of actuation, panel materials, panel geometry, targeted number of inputs and outputs to and from the system, illumination levels (quantity), and luminous distribution (quality). This study specifically investigates independent tilt angles and panel geometry, and their impact on optimizing the quantity and quality of daylighting inside office spaces. Independent tilt angles are an approach proposed in which every other louver has the same tilt angle, either in shading or harvesting position.

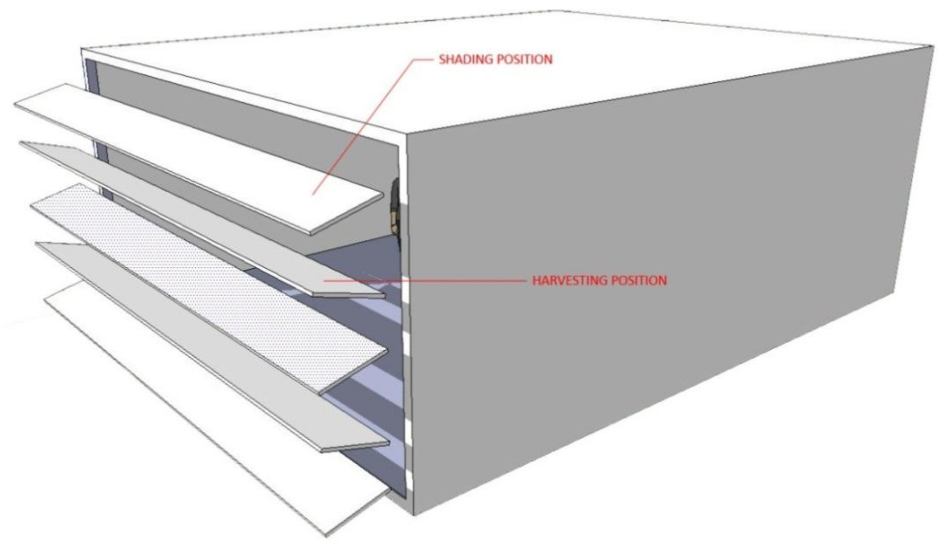

Figure 1-5: Independent tilt angles – the shading and harvesting configurations of different panels actuate independently in a secondary skin system.

1.3. GOALS AND OBJECTIVE

An optimal visual environment in office spaces, achieved through the use of daylight, is crucial for employees' comfort, productivity, and morale[18]. Visual comfort is addressed through many factors, among which are light level (illuminance), luminous distribution, glare, light penetration depth, and direct sunlight[19]. The research goal of this thesis is to design an intelligent dynamic light-deflection system that provides daylight levels within a recommended range, even distribution of daylight inside the space, and penetration of daylight deep into the space, beyond today's normal achievable depth (Figure 1-3). For a better understanding of the goals, the studied parameters are further explained below.

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[18] Dasgupta, *The Impact of Windows on Mood and Performance of Judgmental Tasks*.

[19] Schiler, *Simplified Design of Building Lighting*.

1.3.1 ILLUMINANCE

Different organizations, like the Illuminating Engineering Society (IES) and the National Research Council of Canada (NCR), recommend different light levels for office spaces. The recommended illumination level for an office space according to the Illuminating Engineering Society of North America (IESNA), is 200 – 1500 lux, based on task.[20] The NRC Institute for Research in Construction recommends a level of 400 – 500 lux for general office work.[21] In terms of daylight factor, the recommended percentage is 2-5%. Maintaining a range of 200-1500 lux is the objective of this study, taking into account that values less than 200 lux, and higher than the recommended range, may be acceptable in some areas of the space, under certain conditions, where no activity is assumed to take place.

1.3.2 LUMINOUS DISTRIBUTION

For a better visual environment, the IESNA recommends that, within the occupant's field of view, the ratio between the maximum and minimum illuminance should not exceed 1:10.[22] However, the NRC Institute for Research in Construction recommendation exceeds that of IES, and goes up to 1:20[23], providing an acceptable argument for this high contrast, like highlighting certain objects on the working plane. Sometimes due to high contrast, the occupant perceives

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[20]IES North America, *IESNA Lighting Handbook*.

[21]National Research Council Canada, "NRC Canada."

[22] IES North America, *IESNA Lighting Handbook*.

[23]National Research Council Canada, "NRC Canada."

parts of the space as dark which in reality have sufficient light levels. Maintaining a ratio of 1:10 prevents the false perception of light level inside spaces.

1.3.3 LIGHT PENETRATION

Untreated window openings allow light penetration one-and-a-half times the distance from the floor to the window head. Incorporating light shelves extends the ratio up to twice the distance (Figure 1-3). For example, a 2.20m window head height allows the penetration of daylight into the space up to 3.30m, if using an untreated opening, and 4.40m if using a light shelf. Within the context of this study, the goal is to exceed the 2x ratio – aiming for, at least, two-and-a-half times the vertical distance.

1.4. STRUCTURE AND METHOD

This thesis develops a parametric tool for integrating daylighting performance into the process of kinetic façade design. The tool is intended to be used by anyone - but especially designers - involved in the design process and early-stage decisions. This idea, where innovative, contemporary, exciting developments in façade design are tested for daylight optimization, is a primary concern; it allows designers to find the potential of complex design forms to enhance the indoor luminous environment.

The study focuses on investigating the effectiveness of light deflection by an intelligent secondary skin layer in south-facing indoor spaces. In this study, parametric tools are used to search façade configurations, by pre-defining some parameters denoting intelligence and environmental changes (refer to Chapter 2 for intelligence parameters). The investigation of this topic prior to executing computer simulations is crucial. To address the problem in an efficient manner, the research has been divided into three main parts: investigation (literature study), simulation and documentation, and analysis. Each of the three parts is explained in the section below.

1.4.1 INVESTIGATION

This section provides a complete literature review of the investigated topic and its attributes. Given the investigation of two related topics, 1) intelligent kinetic skins and 2) daylighting performance, the investigation phase is split into two chapters. The literature review of both topics addresses the definition of intelligence within the framework of the study, the use of intelligent skins as light-deflectors, and the performance of daylight-deflection in enhancing the quality and quantity of light in office spaces.

If we are to express the correlation between intelligent skins and daylight enhancement, some points need to be covered in the literature study of the topic. These points directly relate to the intelligence of a building skin and its ability to respond to environmental changes, specifically sunlight. Providing a solid background to the following points builds a concrete foundation for explaining daylight enhancement through the use of intelligent systems:

- What is intelligence?;
- The concept of intelligent responsive systems;
- Intelligence and environmental controls;
- Sensors, data exchange and feedback loops of intelligent systems.

While more points are covered further in Chapter 1, for the interest of the study, the first portion of Chapter 2 covers the intersection of intelligent skins and daylight enhancement; it explains possible techniques for using smart-kinetic systems to adjust daylight quality in indoor spaces. Examples of similar systems and previous work are used to illustrate the positive potential of using deflection techniques in the context of the current technological advancements. The main points covered in Chapter 2 are:

- Benefits of daylighting;
- Daylight fundamentals;
- Performance indicators;
- Deflection techniques.

1.4.2 PROCESSING LOGIC

Within the framework, data processing depends not only on the simulation tool and its calculation capabilities, but also on the pre-defined parameters, based on the desired daylighting performance. The algorithmic components incorporated into the set of parameters force data to flow in certain directions for evaluation purposes. Processing stops when an optimal skin configuration is found by the genetic algorithm component (Figure 1-6).

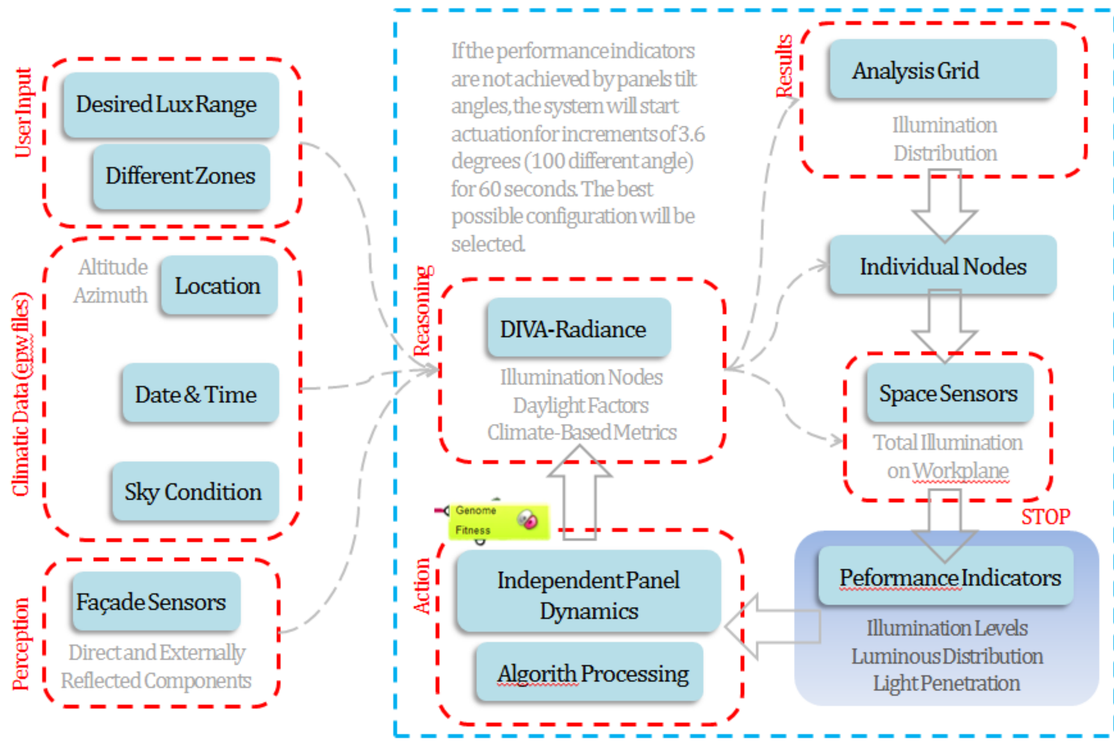

Figure 1-6: System logic – the inputs to the system and the processing of data.

Grasshopper is responsible for setting the input parameters according to the desired luminous environment conditions, and passing these to the daylighting simulation tool, DIVA/Radiance, which then processes the data and sends the results back to Grasshopper for evaluation. Grasshopper compares the results against the pre-defined performance criteria. If the results are acceptable, Grasshopper provides the generated solution as the best possible under the defined simulation conditions. If the results do not match the criteria, Grasshopper sets another scenario for the skin and triggers the simulation tool to re-run a new scenario and generate a new outcome - and so on, until an acceptable result is obtained (Figure 1-6).

The proposed data workflow depends on a solution-based factor, where processing is about finding the optimal solution for a design problem. The system will run “all” possible solutions and then pick the one resulting in the best daylighting performance inside the space. Panel tilt angles are endless; thus, increments of 3.60 degrees will be set to restrict the possible set of solutions to 100.

Different sun conditions are expected to affect the performance of daylighting in the space, and simulating all times of the day is difficult due to time limitations. Consequently, data will be recorded for the following times only: June 21st (summer solstice), December 21st (winter solstice), and March 21st (equinox), each at 9:00am and 12:00pm, for clear sky and overcast sky. At each of the mentioned times, the sun has different solar angle and/or a different direction.

1.4.3 DOCUMENTATION

The integration of four tools was necessary for the objective of this study: Rhino as a modeling tool, Grasshopper as a parametric interface, DIVA 1.1 for daylight simulation, and the Galapagos component as a genetic algorithm problem-solver. A simple example is developed to assess the performance of the system in searching for an optimal solution for skin configurations. Grasshopper is used to identify the input parameters and the evaluation criteria for daylighting assessment, the DIVA component is used to simulate the process of daylighting, and Galapagos, the genetic algorithm component, uses a single-numerical value as a fitness number in search of optimal configuration.

The proposed tool is intended to be used by designers at the early stages of design, to integrate daylighting performance into the process. Such integration could be into the design of interior spaces, building envelopes, and/or orientations. In Chapter 4, the proposed design algorithm used to determine the optimal configuration for a building skin for better daylighting performance is documented. The algorithm is applied to a secondary skin configuration composed of horizontal louvers split into two independent layers; every alternate louver has the same tilt angle. The definition utilizes Radiance as the calculation engine for daylighting, and has been divided into screenshots, which are shown in Chapter 4.

1.4.4 SIMULATION METHOD

As a parametric design tool, Grasshopper allows the creation of a kinetic system that can respond to multiple inputs and outputs through the use of a genetic algorithm. In this tool, intelligent features are expressed as parameters, mathematical functions and benchmarks which make the intelligence of the system limited, but flexible enough for the system to implement certain desired tasks for better daylighting performance. Given that DIVA is a Rhino/Grasshopper plugin, it can easily be integrated into the intelligent part of the algorithmic definition.

Technical difficulties were experienced using DIVA 1.1, the daylighting simulation tool, to extract illuminance values and import them into Grasshopper. The difficulties experienced were due to scripting issues in the component itself. This problem prevented node values from being passed to the evaluation criteria for assessment.

Simulation is vital for this study, to illustrate the objective of the tool. Daylight simulation is a commonly-used technique for predicting the quality of luminous environments, as well as accounting for daylight variability during early design stages. This part provides a set of figures and results generated through executing numerous simulation runs for different skin configurations. Intelligence is defined in the parametric software in the form of preset parameters/constraints, such as the occupants' desired illuminance range. As previously mentioned, Rhino, Grasshopper and the DIVA-plugin are the tools used for simulation in this study. These three tools were designed to work together, and are capable of efficiently exchanging data without the need for more interfaces, making the simulation clean, quick, and reliable.

Modeling building intelligence in computer programs is new technology. Accordingly – within the content of this thesis – intelligence is defined in terms of parameters that can be controlled and referred to as "intelligent enough" to execute required tasks, like setting a parameter for the desired illuminance range. These parameters work in a loop of multiple inputs and outputs which can only be handled by parametric software.

In all simulation runs – as shown in Chapter 5 – a generic office space of 6.00m x 7.50m x 3.00m is used. These dimensions remain fixed throughout the entire study. Though the tilt angle changes, the space dimensions remain the same. The façade is assumed to be fully glazed, using a curtain wall system. However, the elements of the curtain wall system are not taken into account during simulation, in order to minimize calculation time. Initially, the simulation is run for clear and overcast skies for three base test cases: glazing only, light shelf, and horizontal louver system. This part shows the enhancement of daylight performance in relation to changing façade/skin system. It also illustrates the ability of daylight deflection to affect the indoor luminous environment quality.

Afterwards, an intelligent-dynamic system composed of a series of louvers arranged horizontally, each actuating independently (Figure 1-7), is modeled using Rhino/Grasshopper. This is considered to be the main case study of the thesis, on which design alterations will be tested. The panels actuate independently, with the aid of some parametric algorithms. The performance of the skin is shown inside the interior space in terms of quality and quantity of daylighting - which requires establishing some measuring points in the space.

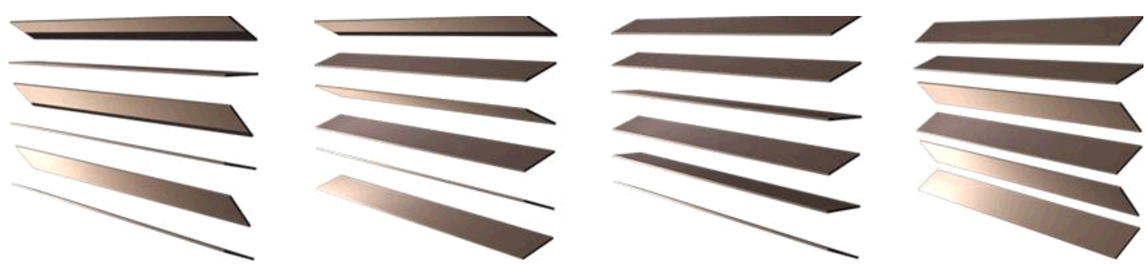

Figure 1-7: Independent actuation of secondary skin panels for better indoor luminous environment quality.

The modeled office space is divided into 36 calculation nodes spread over a grid set at 0.70m, covering the entire surface area of the interior space. Assuming workers do not occupy the entire floor area of an office space, the success of the system is based on achieving the desired performance indicators – previously mentioned – for at least 75% of the office floor area.

Theoretically, the calculation grid is composed of points that read the lighting levels in different positions inside the space. It is expected that readings will vary from one point to another. These points act as the sensors in the simulation. Readings from each point are individually extracted and passed on to set performance criteria for assessment.

A successful run should be able to achieve each of the three indicators for as close as possible to 75% of the entire surface area. Two types of indicators are experienced in this study: individual node indicators, and group indicators. An individual indicator is the illuminance of each point. This does not require evaluation of all points together to see if they fit within the range or not; each node is evaluated independently. Group indicators represent the luminous distribution and the depth of penetration. To evaluate both items, the system is required to look at the results as a collection of nodes, and assess their performance.

1.5. CONCLUSION

Daylighting is a crucial asset in office spaces; it increases the productivity of workers, enhances their morale, and maintains their health[24]. Despite its importance, sometimes designers do not adequately account for daylight during the design phase, which subsequently requires the use of more electric lighting. On the other hand, some architects, like Aalvar Aalto, Louis Kahn, and Le Corbusier, addressed daylight through architecture, emphasizing its importance[25]. This thesis

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[24] Boubekri, *Daylighting, Architecture and Health*.

[25] Schiler, *Simplified Design of Building Lighting*, xi.

explores one example, where innovative-contemporary developments in façade design are considered for better daylighting performance in south-facing office spaces. The whole study is dependent on daylight-deflection techniques to bring daylight levels to desired ranges inside a generic office space. The deflection method is supported by some intelligent features to enhance the operation of the façade system.

The methodology implemented in this study enables designers to account for the performance of daylighting during the early design stage. It also allows them to explore numerous façade designs and their impact on the quality of the indoor luminous environment. Moreover, the technique integrates lighting analysis into the design/modeling tool, which eliminates the need for more interfaces or model export/import procedures. The proposed algorithmic definition is intended to provide flexibility by allowing the possibility of setting different performance indicators – if necessary – based on different design problems.

In the following chapters, an elaboration of the investigated topic is presented, detailing the argument, as well as the intersection of intelligence and daylight-deflection.

2. CHAPTER 2 **INTELLIGENT SKINS**

Applying intelligence to buildings in the form of intelligent façades, sensors, materials, or even building systems, is a discourse taking place in the profession. In this chapter, background research into intelligence in architecture, intelligent applications to buildings, and the human interaction with building systems, is presented.

2.1. OVERVIEW

The word "intelligent" was first used at the beginning of the 1980s to describe buildings, together with the American word "smart"[26]. Since then, building façades incorporating intelligent features have come to be known as "intelligent building skin," where the skin forms the greater part of the intelligent system in the building. Describing a façade as an intelligent element requires the presence of dynamic living capabilities, which enable interaction with diurnal and seasonal changes, and human beings in the surrounding environmental context, in order to achieve a reduction in the energy consumption inside indoor spaces. Intelligence is not an equation of fixed variables; it is a process that is inspired by human intelligence and cognitive capabilities. That being said, the definition of intelligence can be manipulated in different ways according to the designers' intentions and approaches. However, all definitions acknowledge the influence of living organisms in terms of behavior and reasoning.

2.2. INTELLIGENCE IN ARCHITECTURE

Applying intelligence to buildings in the form of intelligent façades, sensors, materials, and even building systems, is a discourse taking place in the profession. People are the establishing point for intelligence in buildings. They are not passive organisms, but adapt to their surroundings psychologically, physically and behaviorally, and often change their environments to be more suitable for them. This is a complex interaction, informed by their senses and mediated by the brain. The brain allows people to reason, perceive, and react to their environment, whether

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[26] Wigginton and Harris, *Intelligent Skins*.

tangible or non-tangible. Humans have always been the inspirational model for considering the application of intelligence in buildings (Figure 2-1).

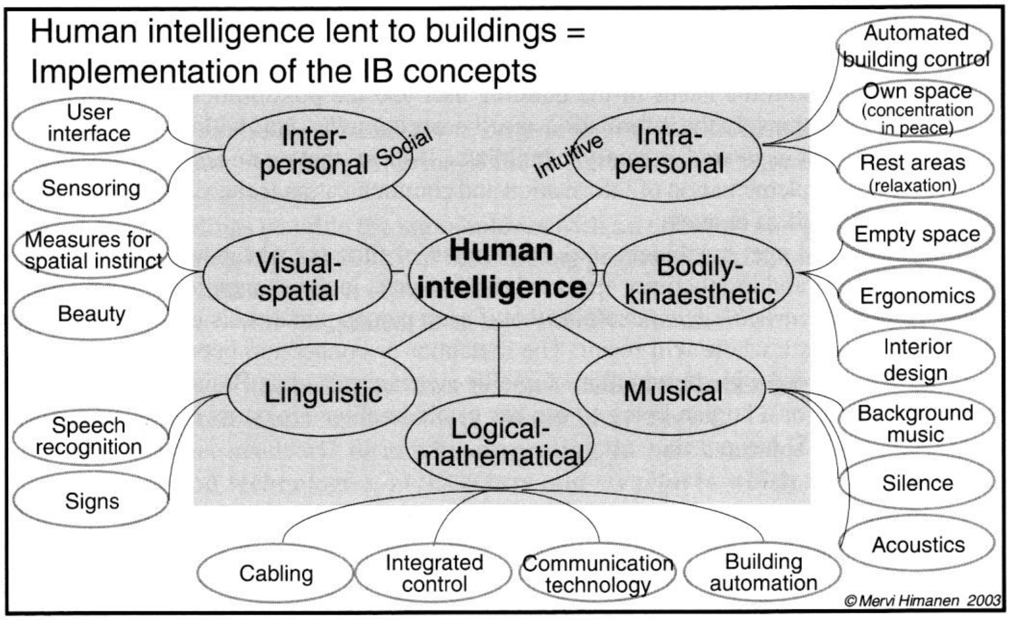

Figure 2-1: Intelligent Building Features and Human Intelligence – the aspects of human intelligence that profoundly impacted the implementation of intelligent features in buildings[27].

The concept of intelligence in architecture should be distinguished from integration or automation in buildings. Intelligence is often referred to by people when objects or elements function using automated features and control systems[28]. They sometimes use the term “intelligent” to describe automated domestic functions at home through a computerized system, like turning on/off the lights, or opening and closing doors. Since these actions are manually triggered by the occupant, they should not be considered intelligent, due to the absence of a system reasoning process (Figure 2-2). In this research, intelligence is based on a

[27] Clements-Croome, *Intelligent Buildings*, 44.

[28] Fox and Kemp, *Interactive Architecture*.

different archetype, which relates to human characteristics and the energy-performance of indoor spaces in buildings, exploring the interaction between the building skin and occupants to provide a better luminous indoor environment. Clements-Croome provides a relevant definition of the term ‘Intelligence’:

> Intelligence is not an attribute, but a complex hierarchy of information processing skills, underlying an adaptive equilibrium between individuals and their environment.[29]

Moreover, the Intelligent Building Institute (IBI) presented one of the first definitions of intelligence in buildings:

> An intelligent building is one which provides a productive and cost effective environment through the optimization of its four basic elements – systems, structure, services, management and the inter-relationship between them. Intelligent buildings help building owners, property managers, and occupants realize their goals in the areas of cost, comfort, convenience, safety, long-term flexibility, and marketability. There is no intelligence threshold past which a building "passes" or "fails". Optimal building intelligence is the matching of solutions to occupant needs. The only characteristic that all intelligent buildings have in common is a structured design to accommodate change in a convenient, cost-effective manner.[30]

Given the scope of this thesis, the above statement presents a valid argument. Assessing the performance of intelligent systems in buildings does not have an absolute benchmark; it is a relative evaluation process that depends on the occupants’ needs and preferences, and the function of the space. Accordingly, the presence of an occupants-model during simulation is necessary for the success of the study. However, simulating such a model in the study would add another layer of investigation, and this has not been included, due to time limitations. Therefore, a compromise has to be made for the simple modeling of intelligent features. The

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[29] Clements-Croome, *Intelligent Buildings*, 5.

[30] “iBuilding Website.”

occupants-model is represented in the form of a set of parameters that resemble the normal working employee preferences. These parameters are simplified factors of the desired luminous environment in general office spaces. *Refer to Chapter 3 for a detailed explanation of the desired quality of luminous environments.*

People involved in the design and construction process can have different views on the performance of an space; the occupant, however, is the one who will truly judge the success of the luminous environment inside the space. Since it is hard to incorporate occupants in the simulation model, the designed algorithmic definition allows for multiple variable inputs to represent changing user needs. This is considered to be an appropriate simplified method for mimicking changing occupants' preferences.

Despite their importance, some buildings tend to ignore occupants' behaviors and preferences, and incorporate responsive features that work based only on environmental changes and climatic conditions. An intelligent building can be looked at as a human body, where occupants represent internal organs, and the envelope resembles the external organ, the skin. Human intelligence is geared to protecting the internal organs, and providing an optimal living environment for them to perform well. Likewise are the building occupants. They need to have a good working environment for better productivity. The occupants' behaviors and preferences are driving factors for building operation - though they differ according to the climate and function of the space. An intelligent building should be able to achieve optimal performance by implementing the following processes:

- Create a relationship between occupants’ behavior and indoor space conditions.
- Automatically adapt and respond to environmental changes and user requirements.
- Expedite cost-effective alteration to occupants’ behavior changes, including changing tasks.

The term “intelligent” has been applied recently to objects that resemble human beings’ behavior. Sometimes called ‘smart’, they tend to process (perception) data like human beings and react (action) based on a process of analysis (thinking). Most of these intelligent features have the same intent, but are different in scale and function. In cars, for example, intelligent driving systems enable cars to automatically detect when cars ahead stop unexpectedly and respond by applying brakes. This feature provides security and comfort to the driver - who is the occupant in this case. The smart driving system evaluates the situation and reacts in a way similar to the way the driver would have reacted. It mimics the expected driver’s behavior for better performance and comfort.

Intelligent buildings should operate in a similar way. They are expected to possess some cognitive features that allow them to perceive data, analyze it, and respond with an appropriate reaction (Figure 2-2). This process can be applied to different aspects of the building operation, among which is the environmental performance of spaces, emphasizing this study’s objective. Embedding the behavior of users, and the changing environmental conditions, into an intelligent-cognitive system may drastically enhance the energy performance of spaces.

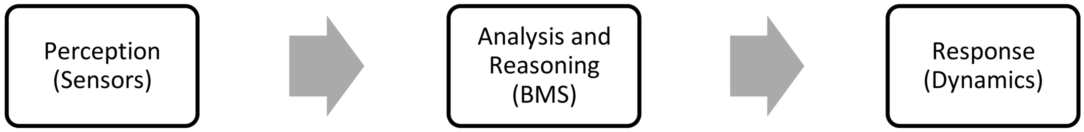

Figure 2-2: Intelligent Process – the data flow process that, generically, identifies a façade as an intelligent feature.

In his book "Intelligent Buildings", Brian Atkin identifies three aspects that should be found in intelligent buildings:[31]

- Buildings should 'know' what is happening inside and immediately outside;
- Buildings should 'decide' the most efficient way of providing a convenient, comfortable, productive environment for the occupants;
- Buildings should 'respond' quickly based on occupants' preferences.

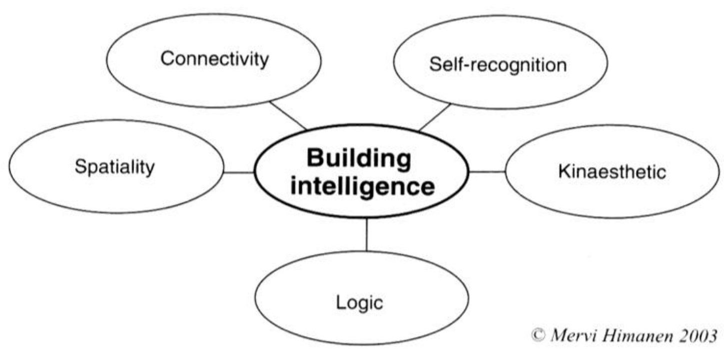

Figure 2-3: Qualities of building intelligence – the main qualities of building intelligence, as defined by Mervi Himanen.[32]

[31] Atkin, *Intelligent Buildings*.

[32] Clements-Croome, *Intelligent Buildings*, 45.

Mervi Himanen divided the qualities of building intelligence into five main categories (Figure 2-3): connectivity, self-recognition, kinaesthetics, logic, and spatiality. Clements-Croome defined each category as follows:[33]

- *Connectivity* relates to how the occupant connects to the system. This could be through speech recognition, automatic control, motion detection, etc.
- *Self-recognition* provides self-consciousness capabilities for the building to detect its current status and interaction level.
- *Spatiality* describes the spatial expression of the architecture.
- *Kinaesthetics* relates to the kinetic capabilities of the system, as well as adaptive technology.
- *Building Logic* expresses the embedded sensors layer that monitors occupants' behavior and reports back to the building management system.

These five factors are taken into consideration within this study with a different approach than that of real-life, due to the limitations of simulation tools, time constraints, and the difficulty of modeling occupants' behavior inside the space. "Connectivity" and "Building Logic" are expressed in the form of a pre-defined set of parameters which reflect the occupants' requirements for better productivity and an enhanced luminous environment. These parameters can be changed at any time prior to running the simulation, which means that the system can be tested for different user preferences, if any. "Self-recognition" and "Spatiality" are expressed in the form of space-sensors/calculation points. Whenever the calculation grids

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[33] Ibid.

go out of the performance criteria range, the system should be able to detect this and work to bring at least 75% of the points into the desired range. Although the method used in this study for simulating one factor of human intelligence inside the space - the varying occupants' desired range of illumination - is not close to reality, it is the best model that can be achieved within the time limitation.

As previously mentioned, intelligent-responsive skins should account for environmental changes and occupants' comfort for better performance. But does this mean that no building skins *without* intelligent features perform well in terms of energy-efficiency? The answer is "no". Environmental approaches have been implemented in the profession before the advanced intelligent technologies discussed here were invented. Architects have long integrated passive approaches into their designs to enhance the performance of the spaces. We, as architects, should acknowledge the importance of previously-designed buildings in providing a concrete foundation for implementing today's technologies in the intelligent-responsive building field. The following section provides two examples of passive environmental controls in architecture which influenced the invention of today's techniques.

2.3. SKIN AS ENVIRONMENTAL FILTER

Given that a façade is the exterior shell of a building, it should act as an environmental filter fine-tuned towards energy-reduction, daylighting, ventilation, and excellent quality of indoor spaces. Throughout history, façade treatments for better performance have been applied to protect indoor spaces from adverse climatic conditions. Many different examples illustrate the façade as an important filter layer, among which are: *Mashrabiyya*, brise-soleil, the trombe wall, high-mass walls, and super-insulated envelopes. Despite the functional differences between the techniques, they all aim for better indoor environments, as well as protecting occupants from unfavorable environmental changes. *Mashrabiyya* and brise-soleil are especially good examples, which attempt to deal with both thermal and daylighting considerations.

Figure 2-4: Egyptian Mashrabiyya – the Mashrabiyya is a great example of an environmental façade treatment for optimizing daylighting, minimizing glare, and driving cool air into the space. The image on the left34 shows the indoor effect of this element, while the image on the right35 shows the exterior look of this ornamental Egyptian icon.

The *Mashrabiyya* is a great example of a passive environmental façade application that controls daylighting and natural ventilation inside a space. Hassan Fathy, the Egyptian leader in

[34] "Sennari House In Cairo: Home to Napoleon's Scholars."

[35] "Mashrabiyya - Wikipedia, the free encyclopedia."

environmental and vernacular architecture, describes the *Mashrabiyya* as a mean of control of severe glare conditions in interior spaces (Figure 2-4). In old times, Egyptians were leaders in inventing environmental performance-based prototypes. They adopted the *Mashrabiyya* in most Egyptian Islamic houses for environmental purposes and comfort of human occupants; in addition, it also reflected local cultural values[36]. While it was a successful approach, widely adopted in Egyptian houses, people are now moving towards implementing more advanced technologies in buildings. The *Mashrabiyya* works inefficiently when windows are open – as seen in the left image of Figure 2-4 – which is necessary for having an outdoor view. The question arises: if it performs so well, why don't we continue using it? Simply put, the answer is: we cannot use this ornamentation piece on all façades. It is a product of the Egyptian culture that was suitable for buildings at that time - the middle ages up to the mid-twentieth century. As seen in Figure 2-4, the design of this element was customized for specific cultures; it is not a generic-modern element that can be fitted into any design - quite apart from its transparency limitation, as previously mentioned.

The Western world has had different approaches for environmental filters. Brise soleil, a pattern of permanent concrete shading elements, is a technique that was popularized by Le Corbusier in buildings with large surface areas of glazing[37]. This performance-based pattern allows the penetration of low-angle sun in winter, for passive heating, and the blockage of high-angle sun during the summer (Figure 2-5). The Gustavo Capanema Palace, designed by Le

[36] Kenzari and Elsheshtawy, "The Ambiguous Veil."

[37] Melendo, Lainez, and Verdejo, "Nineteen Thirties Architecture for Tropical Countries."

Corbusier in 1935, is a famous example that shows the efficient use of brise soleil in Rio de Janeiro. In this example, the brise soleil works well with high-angle sun, however the system is limited in its ability to deal with low-angle sun that may penetrate the space, resulting in an uncomfortable luminous environment. Today's demands for complexity in form and design led to the emergence of another aesthetical limitation of using traditional brise soleil, however this system is found in some old buildings by famous architects like Richard Meier, who used brise soleil in a canopy at the Getty Center in Los Angeles, California.

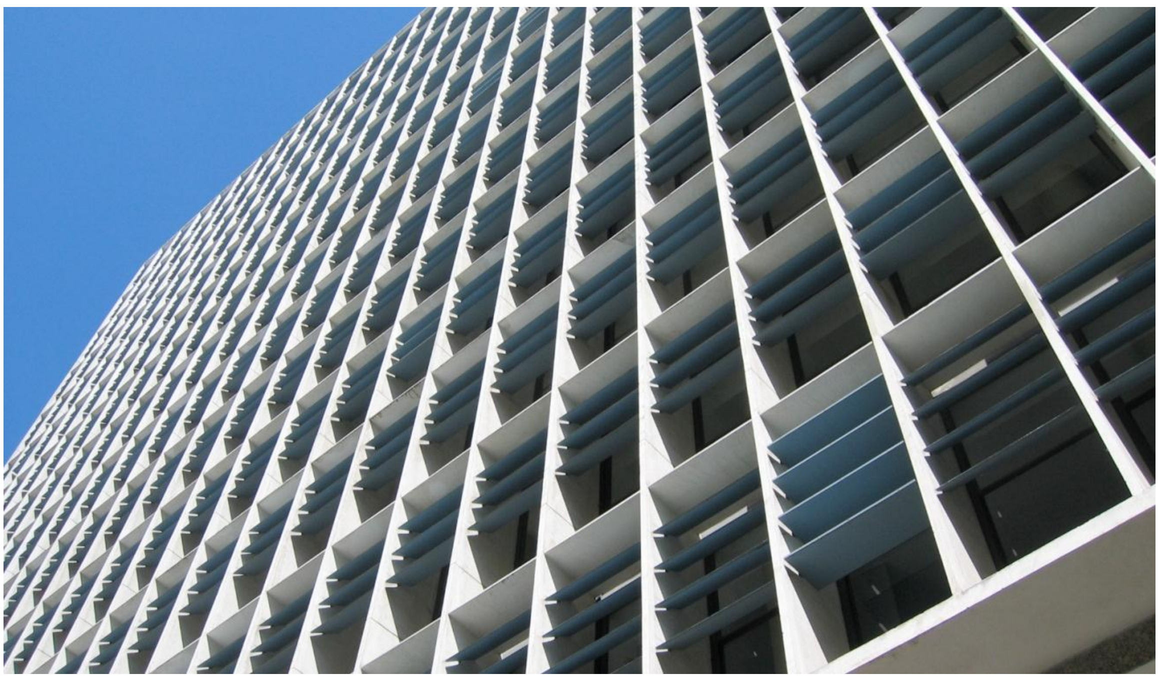

Figure 2-5: Brise Soleil – a modular pattern of fixed concrete shading elements to protect occupants during summer months from heat gain and to allow passive heating during winter months.[38]

Architects have long been able to achieve successful environmental control techniques for "better" performing spaces. They used all available resources – from cultural inspirations to

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[38] "Brise soleil - Wikipedia, the free encyclopedia."

local materials – to achieve better performance. Though these techniques worked well at the time, they do not fit within the needs and preferences of today's occupants, and the design complexity. In other words, though the performance of these systems hasn't changed, other variables have changed which demand better energy performance inside spaces. My hypothesis is that the fast pace of ongoing technological advancement in building systems has made the occupants demand more energy-efficient environments - especially in office spaces - for better productivity and lower running costs. To fulfill the users' needs, designers have explored advanced techniques on building façades, which represent a significant part of any architectural project, besides acting as the medium between the indoor and outdoor environments[39]. However, designers have also developed new systems inspired by historical innovations.

The main case study of this thesis investigates the performance of a brise soleil-like system that possesses dynamic-responsive capabilities. The system uses the same solar shading technique of the brise soleil, and adds to it light-deflection techniques for enhanced luminous environment in office spaces. While the proposed system is inspired by historical innovations, it exploits today's advanced technology by integrating intelligent features into the skin system, which allow independent tilt angle control for each panel.

Building façades are the main manipulators of environmental parameters. If designed efficiently, they should be capable of maintaining an adequate comfort level, by adjusting the impact of natural forces on interior spaces. The envelope's functions include daylighting optimization and

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[39] Wigginton and Harris, *Intelligent Skins*.

glare protection, acoustical barrier, natural ventilation, humidity adjustment, wind protection, visual contact, security and safety, and energy performance. For a building to overcome unexpected and changing adverse climatic conditions, it has to integrate advanced cognitive technology that allows the skin to think, and respond appropriately. For example, a space can detect changes in human behavior - typing or reading, for example - and optimize daylighting levels accordingly.

2.4. INTELLIGENT KINETICS AND DAYLIGHTING PERFORMANCE

The skin is one of the dynamic regulatory organs that allow the body to survive through a wide range of unfavorable conditions. The intelligent behavior of the skin enables adaptation to the surrounding environment by means of physical processes, such as perception, reasoning and action, which allow the human body to overcome adverse environmental conditions. Analogously, the building envelope acts as the medium through which the interior spaces of a building interact with the surrounding environment. Buildings are subjected to a wide range of unfavorable and varying environmental conditions, which requires the envelope to possess intelligent-dynamic capabilities, and automatically respond to environmental changes and user demands.

Smart-kinetic façades are one type of intelligent skin. This is a technological advancement that addresses today's dynamic, constantly-changing activities in order to optimize indoor conditions to meet the user's needs. Smart-kinetics is the flexible adaptability of building façades to respond to changing environmental conditions, taking into account human interaction and behavior. They should be capable of handling the rapidly varying patterns of human interaction in a space.

Smart-kinetics, part of comprehensive intelligent building systems, can be designed as performance-based elements that relate to interaction and responsiveness. They can be part of a primary system, or perform independently as a secondary skin layer. Operable windows are one example of a primary system application, where the windows on the main envelope open and close according to need, while a series of external louvers is a secondary skin application, distinct from the main skin and operating independently. Michael A. Fox, an interactive architecture designer, refers to this type as “dynamic” kinetic typology, where the kinetic elements are part of a bigger system but can act independently.[40] Besides the potential of providing better energy-performance, the use of a secondary skin system allows for more creative designs and skin geometries. That is why a secondary skin system is used in this study. Despite the advanced technology in most buildings, only a few efficiently exploit the presence of an intelligent platform in the building management system, because cognitive-smart applications in buildings haven’t developed enough yet for real-life applications. Though some buildings are referred to as “intelligent architecture,” they can only execute specific tasks, and are unable to act the same way human beings do.

Responsive skin systems first emerged in the form of kinetic technology that works according to a pre-defined set of orders, with no room for processing or reasoning in response to unforeseen

[40] Fox and Kemp, *Interactive Architecture*.

variables. Natural forces are the variables in this case. One example is a dynamic louver system that follows the motion of the sun to prevent direct light inside the space. Such a system is not considered intelligent, as the sun's path is already known and can be programmed into the system, making the louvers move in the same pattern every day. A designer can provide the equations for calculating the sun's position, and the panels will actuate accordingly to face the calculated position. This can be referred to as a *single-input system,* where only one pre-set input is dealt with. Other types of input that can directly affect the occupants in terms of comfort level and productivity include: enhancement of daylight, maximization of daylight, protection from the sun, insulation, natural ventilation, heat collection, heat rejection, sound attenuation, generation of electricity, and exploitation of pressure differentials.[41]

Making a building respond to and account for human needs in its daily operation is one problem where user input is critical. This is obvious when it comes to lighting in office spaces. People usually assume that daylighting will be available when they go to work during daytime. In fact, employees rarely question the quality of the luminous environment inside the space. With today's changing needs, designers have provided occupants with manual control of lighting for better satisfaction, reflecting changing tasks and activities inside the same space. The question is: what happens if we design an intelligent daylight harvesting system that automatically recognizes occupants' demands and reacts accordingly? Will it enhance daylighting performance and satisfy users? My answer would be: yes, it will. This does not mean that good performance is achieved only through intelligent kinetics, however; it is one of many approaches.

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[41] Wigginton and Harris, *Intelligent Skins*, 36.

Within the scope of this research, the critical questions of “where” and “when” daylight is needed are more important than “how much”. Adding the time and place as variables to the equation requires the implementation of an automated-cognitive system that can automatically detect human behavior, and react to it in an appropriate manner[42]. This is what is referred to as an “intelligent” system, after adding the “how much” to the equation.

2.5. TYPOLOGY OF KINETICS IN ARCHITECTURE

Kinetic architecture can be expressed in different forms in buildings, one of which is integrating dynamic features into the façade/skin. Kinetic façade elements are found in various configurations. Below are some configurations of kinetic façades that have been adopted in current buildings. All images in this section have been extracted from a Master of Building Science thesis by former USC student Ryan Hansanuwat.[43]

[42] Wang, *Intelligent Buildings and Building Automation*.

[43] Hansanuwat, “Kinetic facades as environmental control systems.”

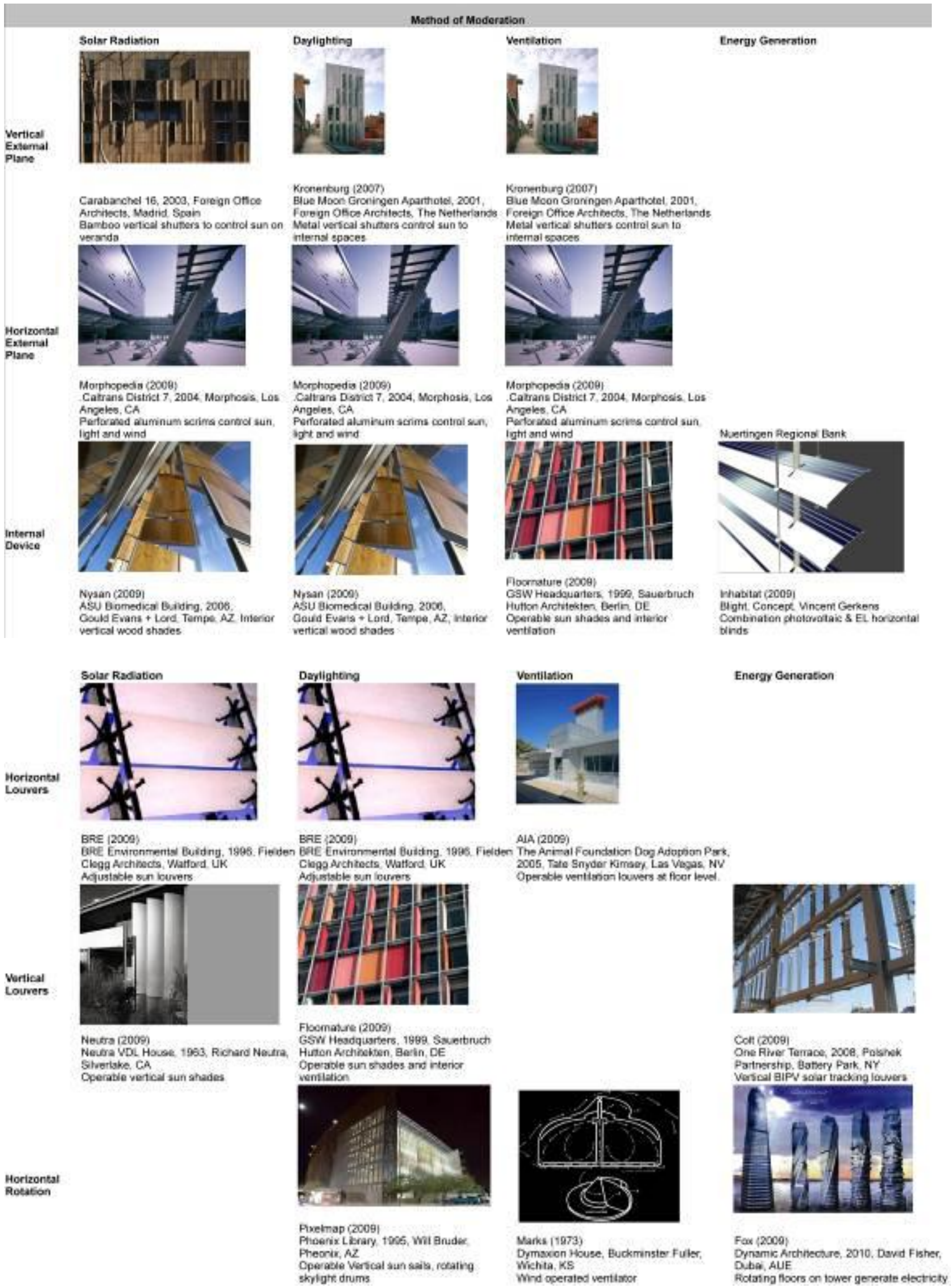

Figure 2-6: Kinetic Typology – The figure shows various typologies of kinetic envelope applications on building facades.

Figure 2-6: Continued

Solar Radiation | **Daylighting** | **Ventilation** | **Energy Generation**

Vertical Rotation

Kronenburg (2007)
Arab World Institute, 1989, Jean Nouvel, Paris, France
Rotating irises operate like camera lenses to control sun exposure on south façade

Kronenburg (2007)
Arab World Institute, 1989, Jean Nouvel, Paris, France
Rotating irises operate like camera lenses to control sun exposure on south façade

Siegel (2009)
EWE Arena, 2006, Arat Siegel, Oldenburg, Germany
Rotating photovoltaic wall tracks sun position

Vertical Sliding Plane

Pixelmap (2009)
Phoenix Library, 1995, Will Bruder, Pheonix, AZ
Operable Vertical sun sails, rotating skylight drums

Horizontal Sliding Plane

Ifp-Weber (2009)
LSV Stuttgart, Hermann- Bosch- Keck Stuttgart

Ifp-Weber (2009)
LSV Stuttgart, Hermann- Bosch- Keck Stuttgart

Ifp-Weber (2009)
LSV Stuttgart, Hermann- Bosch- Keck Stuttgart

Method of Movement

Folding

World Architecture (2009)
Kiefer Technic Showroom, 2007, Ernst Giselbrecht, Graz, Austria
Folding panels can control sun and views

Rotating / Hinged

Fox (2009)
San Francisco Federal Building, 2007, Morphosis, San Francisco, CA
Operable horizontal louvers on computer control to track climate fluctuations

Figure 2-6: Continued

Sliding

ABI (2009)
City of Justice, 2011, Foster + Partners/ABI, Madrid, ES
Sliding linear shading system on roof

Expanding

Muslim (2009)
Medina Umbrellas, Bodo Rasch

Tranforming

Fox (2009)
Bubbles, 2007, FoxLin, Silverlake, CA
Inflatable skins react to touch and tranform to control space

Method of Actuation

Pneumatic Linear Actuation

Fox (2009)
WHITEvoid (Flare), 2004, Christopher Bauder, Berlin
Pneumatically controlled flakes provide varying façade image

Pneumatic Muscles

Fox (2009)
WhoWhatWhenAir, 2006, MIT, Cambridge, MA
Pneumatic muscles to control flexibility of structure

Electronic Linear Actuation

Botta (2009)
Tschuggen Grand Hotel, 2006, Mario Botta, Arosa, Switzerland
Linear acuated wings control light from sails

Figure 2-6: Continued

Electronic Motor Actuation

Kronenburg (2007)
Hoberman Arch, 2002, Chuck Hoberman, Salt Lake City, UT.
Two (2) 30 HP electric motors control tension cables and support weight.

Hyrdaulic Actuation

Dezeen (2009)
Guru Bar, Athens, KLab

Screwdrive

Uni-System (2009)
Residential Observatory, Uni-System

Track

Uni-System (2009)
Reliant Stadium, HOK Sport

Shape Memory Alloy

Fox (2009)
Pixel Skin, 2006, Sachin Anshuman
SMA actuated triangular panels to control internal conditions

Chemical

ODEC (2009)
Passive Solar Tracker

Predictive Control

Neutra (2009)
Neutra VDL House, Silverlake, CA, Richard Neutra

Method of Control

Sensored-Reactive Control

Foxlin (2009)
Kinetic Façade, KDG, Michael Fox

2.6. HUMAN INTERACTION AND CONTROLS

Architectural space can take advantage of an audience locally, regionally, and globally by reconceptualizing the role that the physical environment plays in shaping the viewer's experience.[44]

The quote above is from *Interactive Architecture*, a book by Fox and Kemp which presents the general idea of human interaction in a simple way. Though it sounds simple, the quote carries an important aspect that highlights the significance of human interaction in the field of intelligent skins: it is the users' learning experience. Intelligent architecture should be able to not only expedite lifestyle and behavior, but also to influencing them.[45]

Intelligence in architecture is a two-way process, in which the building learns from the occupants' behavior, and vice versa. The architectural environment can learn from our experiences on a short-term or long-term basis, and can also teach us how to live more efficiently. For example, when direct sunlight hits the working plane, an intelligent system of series of louvers can adjust to overcome the problem of glare or over-illumination. The occupants will learn that, at this time of the day, the sun direction is undesirable for better working conditions. This feedback from the system is significant in teaching occupants how to respond to such situations. Though there could be more complex examples, this one explains

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[44] Fox and Kemp, *Interactive Architecture*, 138.

[45] Ibid., 142.

the simple idea behind a back-and-forth interaction. Another quote from the same chapter in Fox and Kemp's book says that:

To a certain extent, our behaviors are nothing but learned intuitions growing out of our experiences in the world.[46]

As buildings react to changing human behavior, users are challenged with new levels of involvement, understanding and choice. Since this interaction brings new learning experiences to their lifestyle, it is crucial for architects to account for these changing patterns in future designs, and make them geared towards enhancing the working environment in ways other than facilitating the human experience inside the space.

Intelligent architecture responses could be based on either knowledge-based information, sensor-based information, or both. There are many possible mechanisms of human interaction, including *sensors*, which are highly important elements in intelligent environments. Sensors are devices capable of gathering data from the real world, like motion, light, temperature, humidity, sound, and so on.

2.7. MODELING INTELLIGENT KINETICS

Conceptually, the design of kinetic skins is similar to some of the advanced techniques where the designer adjusts parameters to generate a range of outcomes, except that in the case of

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[46] Ibid.

intelligent kinetics there is no final form; rather, the design outcome is a kinetic process, from which multiple forms will occur over the life-cycle of a building.[47] Kinetic skins are generally described as elements integrated into one large system, with adaptable capabilities to create more efficient spaces. The need for better-performing architecture has led to the emergence of kinetics technology, extending beyond conventional techniques. The current trend in the profession is towards incorporating sustainability and technology as integral elements of this larger system, such as intelligence and kinetic applications. In practice, kinetic façades are found in different compositions, where each has its own characteristics, objectives, and impact on the building functionality and aesthetics. They are not necessarily for purely sustainable purposes, but also have aesthetic or socio-cultural value. That being said, modeling intelligence in computer tools is crucial for achieving all the objectives mentioned above.

Modeling intelligence is a special, complicated case of simulation. Commercial computer tools for modeling intelligent architecture are not yet available for designers. Most of the work, time and effort is still in research labs, and firms specializing in this advanced technology. The challenging part of simulating intelligence is in how we can insert human-like agents into a model and make them behave like human beings, and how the computer tool can detect these agents and recognize their behavior as occupants. In the case of real-life simulations, where sensors occupy the space, it is still hard – but not impossible – for the sensors to understand and detect human behavior and emotions, and react accordingly. Many research labs are currently

[47] Moloney, "Building Skins as Kinetic Process: Some Precedent from the Fine Arts."

working on cognitive realization of human behavior, and how sensors can detect facial emotions and human interaction.

Carnegie Mellon Robotics Institute is one of the leading labs in intelligence and human interaction. The Intelligent Agent Technology Lab is developing a research project about "Agent-based Composition of Behavioral Models (ABC)" in which cognitive models are being developed to represent human performance in computer simulations. These models provide a comprehensive representation of the knowledge, behavior, problem-solving skills, and procedures used by occupants in task situations; they take into consideration the intellectual capabilities and limitations of humans. Since there is no "standard" cognitive reference for all situations, problems still persist in developing the human behavior models. The project team analyzed labor-intensive tasks to create a detailed mapping of what humans do to accomplish those tasks. Though this method is time-consuming, effort-intensive, and does not well represent real human behavior, they were able to program human agents with a set of production rules and executable procedures.[48]

This is where the argument lies: how can we rationalize human behavior in the form of rules, procedures and parameters in simulation tools? How simple should it be? Should the model be capable of handling multitasking or single-tasking? In my opinion, a successful comprehensive simulation would be one that exploits more than one human model, each representing a single-task activity. In this study, the behavior of occupants is dependent on the quality of the

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[48] "Robotics Institute: Agent-based Composition of Behavioral Models."

luminous environment. Intelligence has been integrated into the simulation from a single-task perspective for adjusting the quality and quantity of daylighting inside the space; only the desired illumination for occupants has been taken into account in the algorithm. A set of parameters is changed, based on human discomfort assumptions that allow for testing the intelligent skin system against different scenarios of occupant preferences. This is not the only method of simulating human behavior during the early design stage, but it is the simplest.

3. CHAPTER 3 **DYNAMIC DAYLIGHTING**

Bringing daylight into the core of the building is an architectural design challenge that aims for a better visual environment and greater energy efficiency. This can be achieved through the use of advanced dynamic daylight strategies.

This Chapter addresses the specifications for daylighting requirements, providing essential fundamental knowledge for the purpose of this research. It presents background research on daylight and its rewards, daylight qualities, light-deflection strategies, daylight evaluation, and the target benchmark of the design. It is expected that the reader will, at this point, have the necessary information on which the simulation in the following chapter is based.

3.1. INTRODUCTION

In 1973[49], the energy crisis triggered designers' interest in the use of renewable sources of energy, such as solar power, in an effort to reduce non-renewable energy usage. Today, the increasing notion of scarce resources has demanded better daylight strategies to minimize dependency on electric light. Despite the growing notion of energy conservation, daylight is not often used as a major scheme to exploit renewable sources and reduce energy consumption. Many offices rely on electric light during daytime, when it is unnecessary and can be replaced by the integration of daylight strategies. The point is that the notion of energy conservation has not influenced architectural practices enough to adopt advanced daylight approaches in the design. They are required by code to provide certain levels of illumination for different space usage, regardless of the source of light, which gives more room for relying on electric light to compensate for the lack of interior illumination from natural light. New demands by the building industry, and occupants, requires taking daylighting into account during the design phase, to allow more light deep into the core of the building and maximize the percentage of daylit areas.

Daylighting in architecture is a design strategy that exploits natural sunlight in indoor spaces, reducing dependency on electric light, and maintaining human health and a productive work environment during daytime. Daylight refers only to the visible part of the energy spectrum released by the sun (Figure 3-1). It is a source of light that provides full-spectrum light with flawless color rendering.

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[49] Boubekri, *Daylighting, Architecture and Health*, 39.

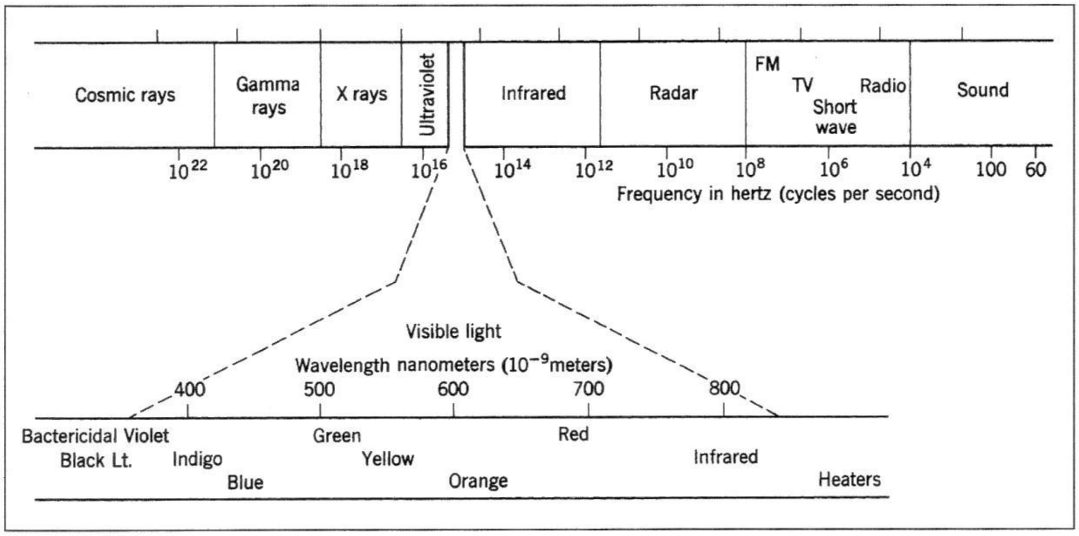

Figure 3 -1: Electromagnetic Spectrum – the range of the visible part of the spectrum.[50]

Daylight, as a free design resource available to architects, enhances the quality of indoor spaces. It invigorates interior spaces, creating a relationship between the occupant and the space. This relationship could be dramatic or intimate, depending on the function of the space. For office spaces, intimacy is required for a better work environment. The art of using daylighting in architecture is not only about allowing light into the space, but providing it without adverse effects. Despite these effects, life cannot continue without daylight, which is required for human health and, now more than ever, for energy-saving approaches.

Successful daylighting is not about increasing opening sizes or adding skylights. It encompasses thoughtful integration of design approaches addressing glare, heat gain, variation in light-

[50] Ander, *Daylighting Performance and Design*, 27.

availability, and direct light penetration. However, in the context of this thesis, only variation in light level, luminous distribution, and penetration depth are tested with different daytime scenarios.

The benefits of a well-designed daylighting concept in office spaces range from better productivity, due to enhanced daylighting quality inside the space, to reduced consumption of artificial lighting. A well-designed space should be able to optimally utilize solar energy through controlling and harvesting daylight. Taking into account the limitations of passive daylight strategies, successful daylight design in office buildings requires going beyond conventional techniques of integrating large openings or light shelves in the architecture. It requires a system that is capable of accounting for unforeseen changes in natural lighting. These changes can range from external elements like reflections from surrounding context, to internal factors like interior surface reflections or changing occupants' activities that require different illumination schemes.

3.2. DAYLIGHT REWARDS

3.2.1 HUMAN HEALTH AND PRODUCTIVITY

Despite the excessive use of artificial light in architecture, people still appreciate the natural gift of daylight, acknowledging its advantages. Natural lighting has always been an important design feature in the building design field. Besides providing a connection to the outdoor environment, it is as vital an element for maintaining human physical health as it is to plant life. Natural light can bring happiness to a space and make people escalate the value of their presence. It also results in an environment with dynamic light conditions, unlike one lit artificially.

Daylight strategies are crucial for sustaining human health, work productivity and a pleasing work environment. There is a disconnection in office architecture and daylighting design which has an extensive impact on inhabitants, affecting body health, productivity, and visual comfort. Such problems arise due to the lack of daylight inside a space, and the extreme reliance on electric light. Most people perceive daylit environments as pleasant spaces for work. In 2003, a student at the Rensselaer Polytechnic Institute carried out a survey of measured negative mood under different daylight conditions. Dasgupta was able to show that, while people working for 20 minutes in an office with a large window during daytime showed a small but significant reduction in negative mood, workers in the same office space during nighttime had no change in their negative mood.[51]

In his book, Koster briefly explained the influence of daylighting on human physiology and psychology. The following quote explains how important natural light is to human health:

> Light synchronizes the human biological clock with day, night and seasonal rhythms. A lack of natural daylight can lead to disorders of the automatic nervous system, loss of energy, fatigue, a tendency towards self-isolation and metabolic disorders. Conversely, intensive light therapy has been shown to support the healing process.[52]

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[51] Dasgupta, *The Impact of Windows on Mood and Performance of Judgmental Tasks*.

[52] Koster, *Dynamic Daylighting Architecture*, 57.

3.2.2 INDIVIDUAL OUTCOMES

In 1996, Veitch and Newsham proposed that lighting quality can be defined as the degree to which the luminous environment supports the following requirements of the people who use the space (Figure 3-2):

- Visual performance;
- Post-visual performance (task performance and behavioral effects other than vision);
- Social interaction and communication;
- Mood state (happiness, alertness, satisfaction, preference);
- Health and safety;
- Aesthetic judgments (assessments of the appearance of the space or the lighting).

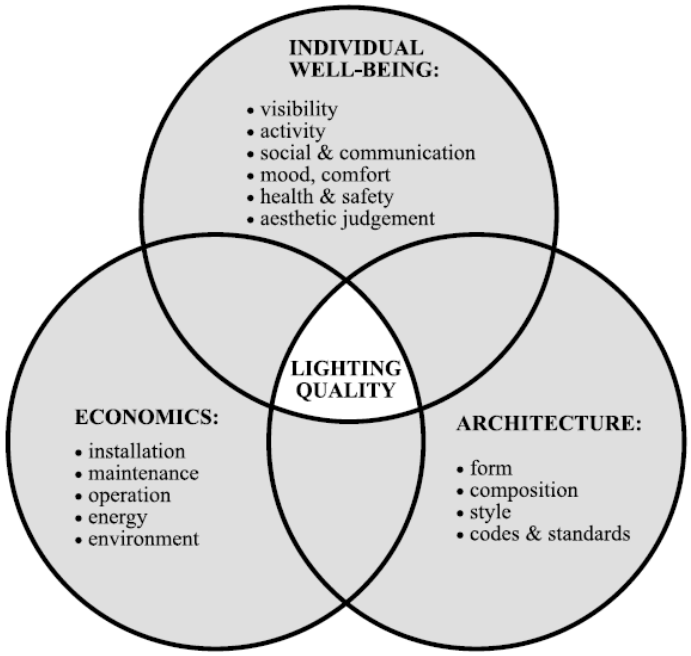

Figure 3-2: Qualities of lighting – Veitch's proposal determines the quality of lighting in any given installation through determining the balance of the (sometimes conflicting) dimensions shown in the diagram.[53]

They also added that the qualities mentioned above do not allow direct measurement of daylighting, but express an emergent state that is created between the occupant in the environment and the light. According to their report, good lighting quality exists when a lighting system creates good conditions for seeing, supports task performance or setting-appropriate behaviors, fosters desirable interaction and communication, contributes to appropriate mood, provides good conditions for health and avoids ill effects, and contributes to the aesthetic appreciation of the space.[54]

[53] Veitch, "Psychological processes influencing lighting quality," 19.

[54] Veitch, J. A, *Determinants of Lighting Quality I*.

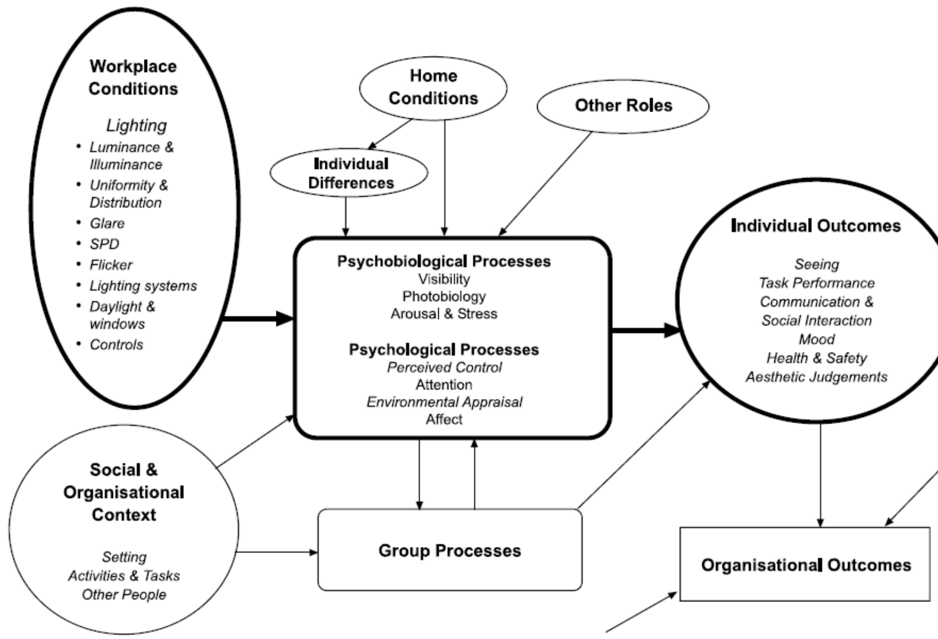

Figure 3-3: Individual Outcome – the influence of various factors, including lighting conditions, on the individual outcome.[55]

3.2.3 ENERGY USAGE

Lighting accounts for 30-50% of the energy use in commercial buildings.[56] Significant energy-savings can be obtained if daylight strategies are incorporated into the architecture, primarily for use during daytime when sunlight is available and the use of artificial light is unnecessary.

Daylight design strategies can reduce the extensive use of electric light inside office spaces if well designed, as well as indirectly increasing savings due to changes in thermal loads. Controlling sunlight penetration into a space is a broad strategy that not only guarantees

[55] Veitch, “Psychological processes influencing lighting quality,” 20.

[56] Phillips, *Daylighting*, 38.

adequate light levels, but also reduces solar heat gain, which is preferred in hot climates. However, savings vary by building orientation, season, and façade design.

The Environment Department of Great Britain carried out a comparative study on various façade types (Figure 3-4). The study shows room for decreasing lighting loads through the design of better performing façades. Lighting needs for a cellular plan are the least significant, while an open office space required a greater lighting load for a better work environment. In cellular plans, more vertical surfaces could be used to bounce light and provide more illumination, which is not the case in open offices. Adding movable reflective surfaces on façades could be a good solution for open space offices.

While a passive system can result in considerable energy savings, active approaches can go beyond these conventional numbers, simply because they are capable of adapting to the major source of daylight - the sun - which is a dynamic natural force that changes location over the course of the day.

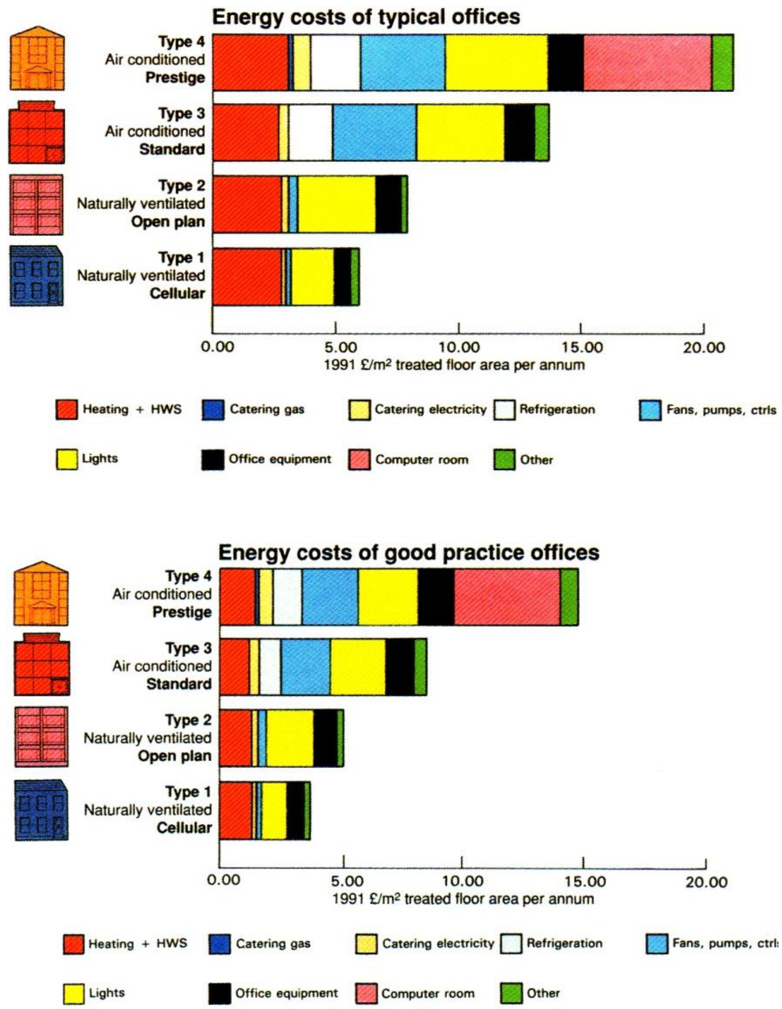

Figure 3-4: Energy Usage in Offices – the breakdown of energy usage costs, including lights, for typical and good practice offices.[57]

3.3. DAYLIGHT FUNDAMENTALS

3.3.1 SOURCE OF LIGHT

Daylight, an important requisite in office buildings for efficient task execution and a satisfying visual working environment, is usually a combination of direct sunlight, diffuse light from the

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[57] Koster, *Dynamic Daylighting Architecture*, 23.

sky, and light bounced off surfaces. One can distinguish daylight sources into two main types: primary sources, and secondary sources. Primary sources are sources that release light like the sun and sky, while secondary sources are sources that reflect light but do not produce it, like surfaces and objects.

Sunlight passes through various layers in the atmosphere before hitting the built environment. The intensity of solar radiation is dependent on various factors, among which are the sun's position, clouds, gaseous and particulate pollution, and thickness of the air mass (Figure 3-5). Daylight delivers full-spectrum light for flawless color rendering, as well as providing the best visual conditions in a luminous environment for the human eye.

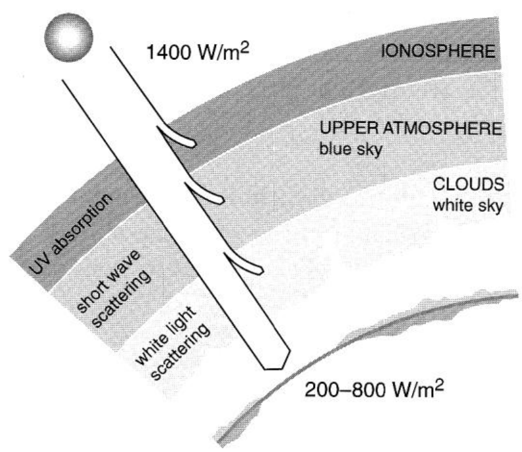

Figure 3-5: Atmosphere Layers – the layers through which light passes before arriving on the work plane.[58]

[58] Baker and Steemers, *Daylight Design of Buildings*, 31.

Considered a secondary source of daylight, surfaces are the surrounding context, including the ground and neighboring façades, and interior surfaces in the space. The finish material of each surface affects the amount of light bounced off of it. The brighter the surface, the more light is bounced off. Therefore, daylight at a point in a space is composed of the following components:

- Direct sunlight (in the case of a clear sky and no blockage);
- Diffused light from the sky;
- Externally reflected components;
- Internally reflected component.

Considered the only source of natural light, the sun has high luminous efficacy. On a clear day, direct sunlight can illuminate a horizontal plane up to 10000 foot-candles. On an overcast day, sky luminance may reach up to 20,000 cd/m^2, while the luminance of a clear sky reaches 50,000 cd/m^2.[59]

3.3.2 PROPERTIES OF DAYLIGHT

Visual and thermal problems always accompany the penetration of daylight into a space, and are perceived by occupants as unfavorable luminous and thermal conditions. Insufficient lighting, illumination beyond recommended ranges, or direct sunlight falling on working planes are among the major problems caused by daylighting. More problems are addressed in terms of characteristics or variables (Figure 3-6), thereby controlling the quality of the luminous environment. Each parameter is looked at as a design problem that results in an adverse condition, requiring the adoption of design strategies to overcome it.

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[59] Koster, *Dynamic Daylighting Architecture*, 54.

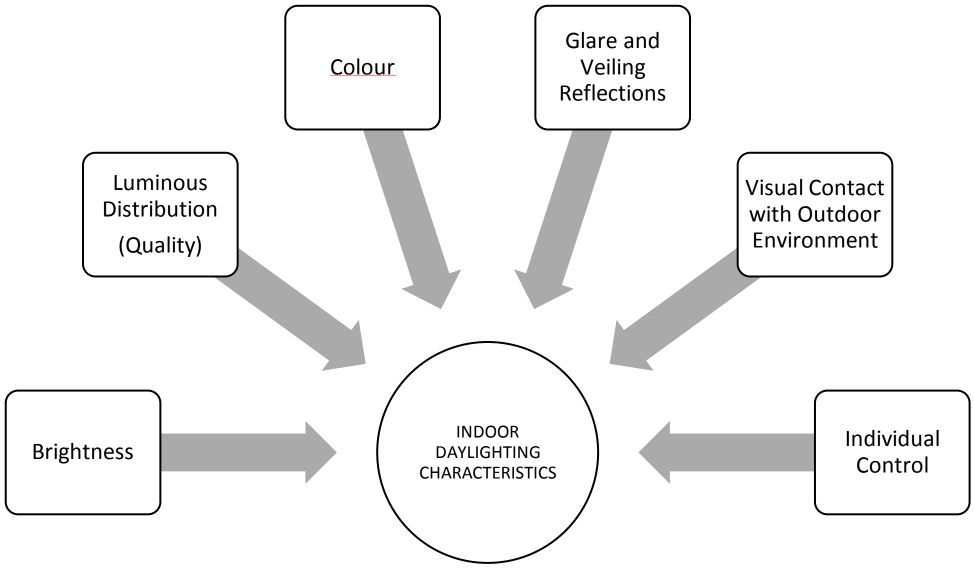

Figure 3-6: Daylighting Characteristics – the characteristics of daylighting that have impact on occupants' productivity and visual comfort in indoor spaces

Within the scope of the study, the two main factors that are tested are the exterior dynamic-intelligent skin that harvests and controls the penetration and direction of light, and the complex panel geometry. The conventional horizontal louver linked to an intelligent system is the first phase of the study, while the second phase tests various panel geometries linked to the same system of a real-life building.

Within the context of this research, the quality of daylight in a space is addressed through three main aspects: the illumination levels range, the light penetration depth, and the luminous distribution in the space. In office buildings, the use of daylighting has a considerable impact on the energy consumption of the building. However, flooding the space with daylight neither achieves the recommended illumination range nor provides a good visual environment. It may result in over-illuminating the space, leading to many visual, thermal and energy problems. Daylight harvesting strategies may efficiently control the penetration of light into the space, controlling the quality of the luminous environment accordingly.

3.3.3 FORM AND ORIENTATION

Orienting a building in relation to the surrounding context and the known path of the sun is a crucial concern in the design process, allowing the designer to either let more light into the space, or to prevent it (Figure 3-7). There are different techniques for controlling light amounts in spaces, among which horizontal and vertical fins are the most famous. Though they have been very successful in solar shading and light deflection throughout the past decades, designers are rethinking this technique with an eye to using advanced integrated technology. While vertical fins are efficient blockers on east and west façades, where the sun angle is low, horizontal panels are the most effective for south-facing spaces, due to high-angle sun. These strategies are commonly known, because of the constant path of the sun, which moves in the same route every day, every month, and every year.

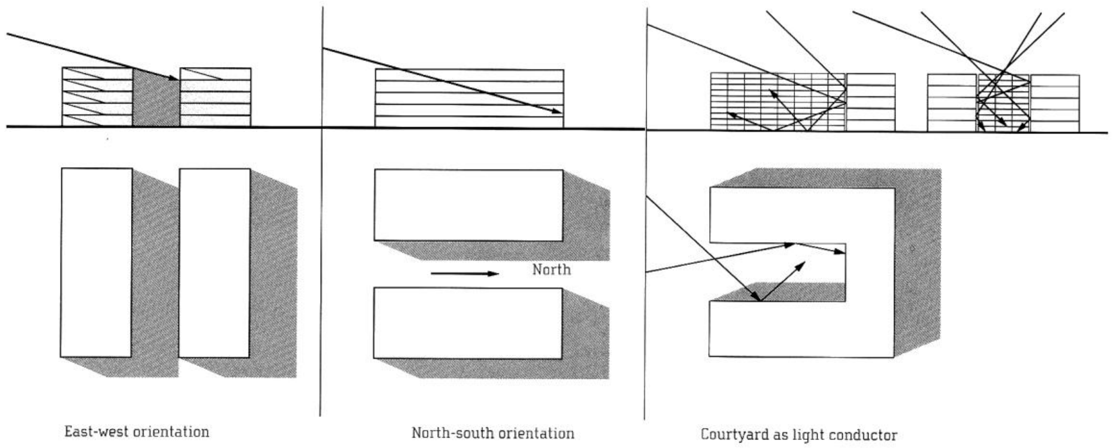

Figure 3-7: Building form and orientation – various building forms and orientations, and their impact on daylight penetration into the space.[60]

Building form determines the surface area exposed to the outdoor. The more compact the building plan, the less daylit space exists (Figure 3-7). The depth of the plan and section determines how deep the light will penetrate into the space. As shown in Figure 3-7, a north-south orientation has a deep width, which minimizes the penetration of sunlight into the space. Conversely, an east-west orientation has a shorter width, allowing sunlight to hit most of the indoor space. Generally, orienting the longer side of the building towards the sun is a favorable idea. Also, the use of courtyards produces greater light-deflection on the building exterior surfaces, and directs light into more space. This strategy also increases the perimeter of the building that is exposed to sunlight.

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[60] Ibid., 69.

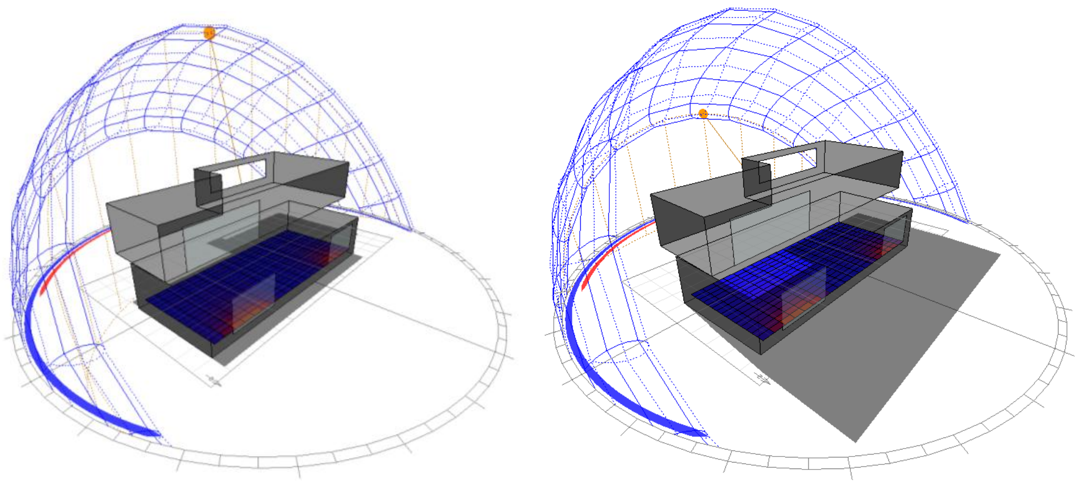

Figure 3-8: Sun path diagram – the annual sun path for Los Angeles. The high-angle sun represents August, while the low-angle sun reflects the sun location in December, both on the same day, at the same time.

Given that the path of the sun is precisely known, designers are able to calculate the altitude and azimuth of the sun on any specific date and time in any location worldwide (Figure 3-8). They can predict the best building orientation, and generate diagrams displaying the sun's location and annual shading range. Using numbers from the charts, equations, and tables, the amount of illumination inside a space can be manually calculated. The fluctuation of the amount of sunlight hitting a space is dependent on the orientation of space, location, and month, day and time of the year. During the summer, a larger surface area of a building is exposed to the sun - represented by the blue line on the horizontal plane in Figure 3-8, while the red line, representing the sun range during the winter, has a shorter period.

3.3.4 INTERNAL FACTORS IMPACT

In addition to the external factors mentioned above, lighting design is directly related to some internal parameters which are present inside a space itself. Manipulating these parameters changes the quality of the interior luminous environment. Required illumination differs according to task; the more complex a task, the more light is likely to be required. Given that light in general office spaces is task-oriented, all parameters of task execution should be precisely defined. Some of these parameters are known and unlikely to change, like the working plan of a computer desk - which is always around 2’ 7” (90 cm). Illumination levels are also dependent on materials - specifically surface reflectance, dirt accumulation, and room dimensions. These factors should be defined prior to beginning the design process. Furniture distribution in relation to glazing location is crucial in daylighting. A favorable practice for designing is to change one variable at a time, and in this study furniture has been omitted from the simulation, for quick-easier runs, intending to bring as much surface area as possible into desired conditions, regardless of the occupancy status.

3.4. PERFORMANCE INDICATORS

3.4.1 PREVIOUS WORK

In section 3.2.1, the importance of daylighting to human health was highlighted as a necessary requisite for a better, more productive work environment, and greater energy savings. However, there are no exact measurements that can directly quantify this impact. Several studies on the topic of daylight quality and performance have been conducted in the past ten years. Several research labs dedicated sections to lighting research, including daylighting. Various studies showed different assessment criteria for the quality of daylight inside a space. No disagreement appeared in any of this literature on the basic evaluation factors, such as illumination levels, luminous distribution, and glare. Nevertheless, each researcher added their own factors, depending on the experimental conditions and the objectives of the study.

In 1994, the committee of quality of the visual environment of the Illuminating Engineering Society of North America (IESNA) identified ten aspects that impact lighting quality, and can also be used to evaluate daylighting quality:[61]

- Brightness (comparative luminance) of room surfaces;
- Task contrast;
- Task illuminance;
- Source luminance (glare);
- Color spectrum and color rendering;
- Daylight (view);
- Spatial and visual clarity;
- Visual interest;
- Psychological orientation;
- Occupant control and system flexibility.

In the IESNA assessment criteria, factors like visual interest, psychological orientation, and occupant control, are hard to evaluate, due to the various personal variables involved in each factor. The remaining factors can be evaluated through calculations and computer simulations. However, not all factors can be studied within the context of this research, due to time limitations. Nonetheless, these criteria provide a sound assessment of indoor daylight performance in office spaces, if all factors are taken into account.

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[61] Dubois, "Impact of Solar Shading Devices on Daylight Quality," 24.

In 2001, Marie-Claude Dubois conducted doctoral research on "Impact of Solar Shading Devices on Daylight Quality," with a focus on office spaces. She came up with simpler assessment measures for evaluating the performance of daylight inside a space. Dubois defined five main indicators affecting the luminous environment in office spaces:[62]

- Daylight factor;
- Absolute work plane illuminance;
- Illuminance uniformity on the work plane;
- Absolute luminance values on the vertical plane;
- Luminance ratios between the paper task, the walls, and the video display terminal (VDT) screen.

Within the framework of this thesis, three conditions were selected, based on the literature review of the topic and previous work done in the same field: illuminance, luminous distribution, and light penetration.

3.4.2 ILLUMINANCE

Different organizations recommend different light levels for office spaces. The recommended illumination level according to the Illuminating Engineering Society of North America (IESNA) for a typical office space is 200-500 lux.[63] The NRC Institute for Research in Construction

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[62] Ibid., 13.

[63] IES North America, *IESNA Lighting Handbook*.

recommends a level of 400-500 lux for typical office work.[64] In terms of daylight factor, the recommended percentage is 2-5%. This study targets a level of 300 lux, taking into account that values less than 200 lux and higher than the recommended range may be acceptable in some areas of the space, under certain conditions. In general, the IES lighting handbook defines values ranging from 100 to 1500 lux[65] as acceptable (Figure 3-9). Evaluation of the simulation runs will be based on this range.

Type of Space	Guideline (footcandles)[a]
Offices	
Corridors, stairways, washrooms	10–20[b]
Filing cabinets, bookshelves, conference tables	30
Secretarial desks (with task lighting as needed)	50–70
Routine work (reading, transcribing, filing, mail sorting, etc.)	100
Accounting, auditing, bookkeeping	150
Post offices	
Storage, corridors, stairways	20
Lobby	30

[a] To convert to lux, multiply the value by 10.76.
[b] In no case less than one-fifth of the level in adjacent work stations.

Figure 3-9: IES Lighting Handbook Illumination – the recommended range of illumination in footcandles for office spaces.[66]

3.4.3 LUMINOUS DISTRIBUTION

For a better visual environment, the IESNA recommends that, within the occupant's field of view, the ratio between the maximum and minimum illuminance should not exceed 1:10.[67]

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[64] National Research Council Canada, "NRC Canada."

[65] Bradshaw, *The Building Environment*, 259.

[66] Ibid.

However, the NRC Institute for Research in Construction recommendation exceeds that of IES and goes up to 1:20[68], providing an acceptable argument for this high contrast, like highlighting certain objects on the working plane. Sometimes, due to high contrast, the occupant perceives parts of the space to be dark, which in reality have sufficient light levels. Maintaining this ratio prevents the false perception of light levels inside spaces.

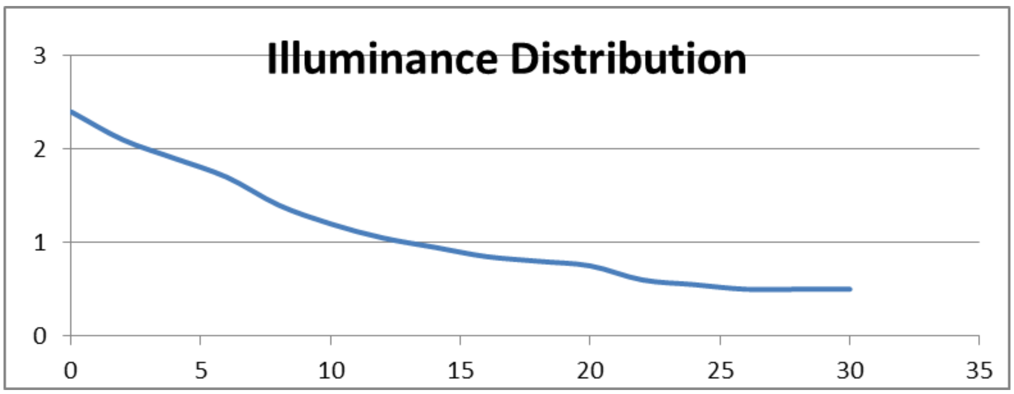

Figure 3-10: Illuminance Distribution – typical fall-off curve-shape of illumination inside a space.

Daylight factor (D) = E_i / E_a x 100%

E_i: intensity of interior illumination

E_a: intensity of exterior illumination

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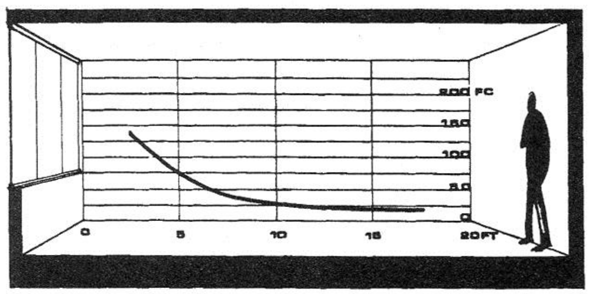
[67] National Research Council Canada, "NRC Canada."

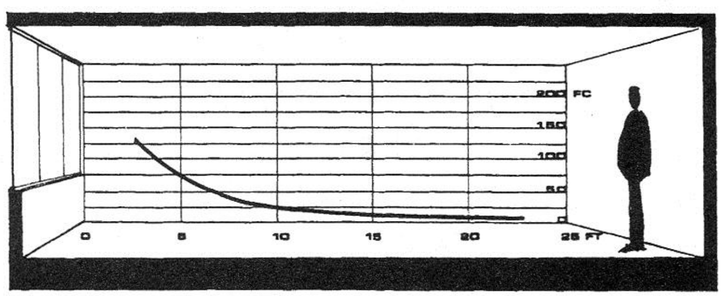
[68] Ibid.

3.4.4 DEPTH OF LIGHT PENETRATION

An untreated window opening allows light penetration one-and-a-half times the distance from the floor to the window head. Incorporating a light shelf extends the ratio to up to twice the distance. For example, a 2.20m window head height allows the penetration of daylight into the space up to 3.30m if using untreated opening, and 4.40m using a light shelf. Within the context of this study, the goal is to go beyond the 2x ratio, aiming for at least two-and-a-half times this vertical distance.



10'x20'space



10'x25'space

Figure 3-11: Illuminance-Depth Relationship – typical fall-off curve of illumination inside a space, and its relationship to room depth. The deeper the room the less illumination at the back[69].

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[69] Ander, *Daylighting Performance and Design*, 13.

3.4.5 EVALUATION CRITERIA

Dubois also included in her dissertation work evaluation criteria for the five indicators that she was testing (Figure 2-7). She provided numerical values for each category, and their corresponding interpretation. Based on the objective of this research, only the first three factors are considered for evaluation parameters - in addition to light penetration depth, which was not taken into account.

#	Performance indicator	Interpretation
1	**DAYLIGHT FACTOR**	
	< 1 %	unacceptable
	1-2 %	acceptable
	2-5 %	preferable
	> 5 %	ideal for paper work / too bright for computer work
2	**WORK PLANE ILLUMINANCE**	
	< 100 lx	too dark for paper and computer work
	100-300 lx	too dark for paper work / acceptable for computer work
	300-500 lx	acceptable for paper work / ideal for computer work
	> 500 lx	ideal for paper work / too bright for computer work
3	**ILLUMINANCE UNIFORMITY ON THE WORK PLANE**	
	$E_{min}/E_{max} > 0.5$	acceptable
	$E_{min}/E_{max} > 0.7$	ideal
	$E_{min}/E_{av} > 0.8$	ideal
4	**ABSOLUTE LUMINANCE**	
	> 2000 cd/m^2	too bright, anywhere in the room
	> 1000 cd/m^2	too bright, in the normal visual field*
	< 500 cd/m^2	preferable
	< 30 cd/m^2	unacceptably dark
5	**LUMINANCE RATIOS**	
	$0.33 < L_{paper\_task}/L_{VDT} < 3$	acceptable
	$0.33 < L_{paper\_task}/L_{adjacent\_wall} < 3$	acceptable
	$0.33 < L_{VDT}/L_{adjacent\_wall} < 3$	acceptable
	($L_{paper\_task}/L_{VDT} < 0.33$ or > 3	unacceptable)
	($L_{paper\_task}/L_{adjacent\_wall} < 0.33$ or > 3	unacceptable)
	($L_{VDT}/L_{adjacent\_wall} < 0.33$ or > 3	unacceptable)

*The normal visual field is the area that extends 90° each side horizontally, 50° upwards and 70° down from the horizon (NUTEK, 1994).

Figure 3-12: Interpretation of Indicators – evaluation criteria for each of the indicators affecting indoor daylight performance. Only factors one thru three are considered within the scope of this work.[70]

[70] Dubois, "Impact of Solar Shading Devices on Daylight Quality," 14.

3.5. DAYLIGHT-DEFLECTION TECHNIQUE

3.5.1 EVOLUTION OF LIGHT DEFLECTION

The concept of light deflection goes back to 1801[71], when Johann Soldner, German physicist, mathematician and astronomer, concluded that light would be diverted by heavenly bodies. He was able to calculate the amount of sunlight ray deflection caused by a star. It was not until 1919 that British astronomers were able to attempt the first measurement of the relativistic phenomenon of light diversion. Their conclusion was dependent on the fact that light-deflection changes the perception of astronomical observations.

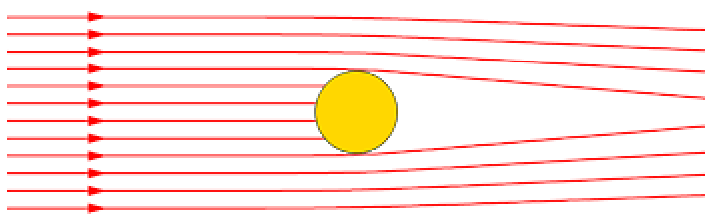

Figure 3-13: Simple Light Deflection – the basic concept of light-deflection in 1919.[72]

> The "location of a star in the night sky" is simply short-hand for "the direction from which that star's light reaches us". Starlight that passes close to the sun before reaching us gets deflected, as sketched in the figure above (but by a much smaller amount than is shown there). This starlight will thus reach us from a slightly different direction than when the sun is in some different region of the sky. Accordingly, the star's position in the night sky is shifted slightly.[73]

This inspiring concept of exploiting sunlight had a great impact on architecture. Designers extensively adopted this technology in different forms of daylight controlling systems, such as light-pipes, prismatic louvers, and anidolic lighting systems. This technology plays a great role in

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[71] Soldner, J. G. v., "On the Deflection of a Light Ray from its Rectilinear Motion."

[72] "The light side of gravity — Einstein Online."

[73] Ibid.

redefining the importance of daylighting strategies in architecture, and the possibility of maximizing their usage.

3.5.2 CONCEPT OF DAYLIGHT DEFLECTION

Daylight deflection is the technique of re-directing light into a space in a controlled fashion. This technique has been around since the early use of venetian blinds and light-shelves, which depend on bouncing light back into the outdoor environment. These were not referred to as light-deflectors, though, because their main purpose was *blocking* light. Solar shading and conventional venetian blinds efficiently block direct light, but they do not harvest and re-direct it into the space, thereby losing it to the outdoor environment: a waste of energy. Light deflectors block light by re-directing it outside of the occupants' line of vision, and into the space, protecting inhabitants from glare and direct sunlight.

> Daylight deflection is re-direction of incoming natural light through glass systems containing reflecting and light-guiding or light-diffusing surfaces or gratings. Such systems distribute and diffuse the incoming light in a room, ensuring even illumination with no glares or heavy shadows.[74]

3.5.3 DAYLIGHT HARVESTING USING LIGHT-DEFLECTORS

Daylight deflection is a process achieved using reflective shading devices. It can be static or dynamic. As a technological advancement in daylighting design, the purpose of daylight deflection, besides protection against glare, is to control the intensity and direction of light, and its distribution. This can be achieved by controlling the amount of light penetrating through the building envelope, and reflecting unnecessary light back into the outdoor environment. In his

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[74] "Thiele AG - Transparente Innovation."

book, Koster mentions that the efficiency of a daylight deflection system is directly related to the following parameters:[75]

- Type of the deflector;
- Physical properties of the deflector;
- Location of the system in the building;
- Mounting position relative to the space.

Koster also mentions that the purpose of light-deflection techniques is to provide protection against solar heat and glare, and to provide a controlled supply, thereby improving indoor illumination. The advantage of light-deflection techniques over solar shading is their ability to work as a control layer, and to strengthen weak daylighting, specifically at the back of a space.

> In practice, the shading systems are closed during periods of the largest solar gains (direct solar radiation), darkening the interior and resulting in a need for artificial lighting. This is a waste of energy that could be avoided, especially since the total electrical energy for lighting is transformed into heat that must be removed in summer by an energy-intensive interior cooling system.[76]

The above statement addresses the need to exploit light deflection and to control light penetrating into the space. Instead of possessing only one function, efficiency requires that shading devices minimize solar heat gain and control light by blocking it or bouncing it off appropriately into the space, without wasting free solar energy and consuming more electric light.

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[75] Koster, *Dynamic Daylighting Architecture*, 80.

[76] Ibid., 13.

As previously mentioned, daylight-deflection is the process of re-directing light into the space or back into the outdoor environment. However, the use of both strategies in a combined scheme is possible, and may prove more efficient (Figure 3-14). Given simple light reflection techniques, this combination may allow for efficient daylight optimization inside a space, due to a combined configuration of blocking unnecessary light, and harvesting it in an appropriate way that does not adversely affect the occupants' working environment.

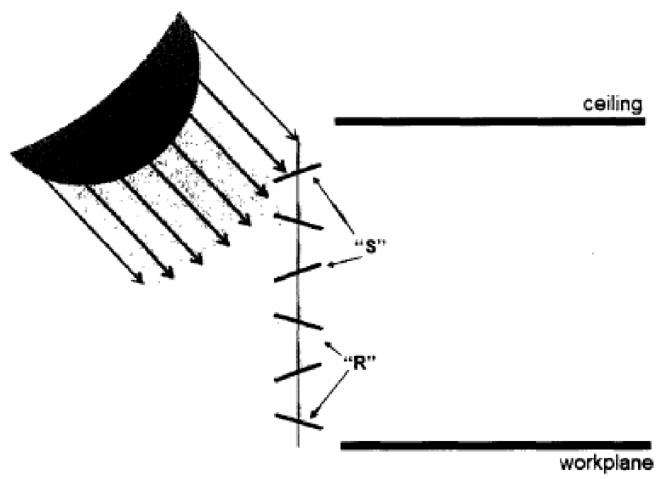

Figure 3-14: Combined Configuration – the shading and harvesting configuration of different panels actuating independently in a secondary skin system.[77]

[77] McGuire, "A system for optimizing interior daylight distribution..."

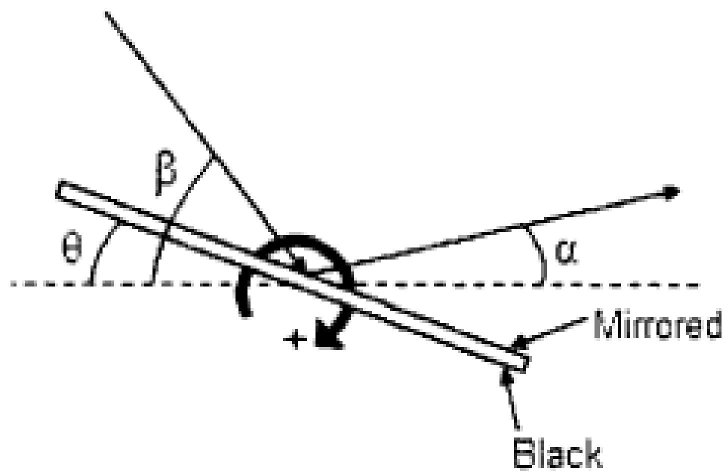

Figure 3-15: Angles Calculation – incident and reflected angles.[78]

Equations used for calculation[79]

$$\boldsymbol{\alpha = 90^\circ - \arctan\left(\frac{d}{h}\right)}$$

$$\boldsymbol{\alpha = \beta + 2\theta}$$

$\boldsymbol{\beta}$ Incident Solar Angle

$\boldsymbol{\theta}$ Louver Angle

$\boldsymbol{\alpha}$ Redirected Angle

$\boldsymbol{d}$ Room Depth

$\boldsymbol{h}$ Window Height

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[78] Ibid.

[79] Ibid.

In the field of daylight harvesting, there are clearly many ways of controlling and directing the light; among which are the actuation pattern, geometry of panel, size of panel, orientation of space, reflectance of materials, and the panel adaptability to intelligently respond to changes. In the design stage of this study, some of these ways may be considered for enhancing the skin design of real-life architecture.

As previously mentioned, daylight-deflection is re-directing light into the space or to the outdoor environment. However, the use of both strategies in a combined scheme is possible and may prove more efficiency (figure 3-14). Given the simple light reflection techniques, this combination may allow for efficient daylight optimization inside the space due to a combined configuration of blocking unnecessary light and harvesting it in an appropriate way that does not destruct the occupants' working environment.

Bring it in high. Bounce it or filter it. Control it. Harvest it.[80]

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[80] Schiler, *Daylight Harvesting*.

4. CHAPTER 4 **INTELLIGENT SKIN DESIGN TOOL**

Simulating intelligence in building skins and testing it for dynamic daylighting performance is a challenging study in terms of simulation parameters and the logic of data processing. Rationalizing the logic processing in the form of parameters is the key element for the success of the simulation process.

This chapter describes the specification of the proposed algorithmic design tool for simulating intelligent kinetic elements on building facades and their impact of daylighting performance.

4.1. INTRODUCTION

Software advances have drastically enhanced the design process in the profession. The more parameters we are able to control and to procure, the more solutions generations the software can produce. The overwhelming responsibility of data exchange between various interfaces in the design process is crucial for efficiently exploiting the design tool. The demand for integrating performance-based techniques into the early design stage requires a bidirectional exchange of data, where information flows back-and-forth between multiple interfaces.

This chapter describes an extensible parametric design tool for assessing the performance of kinetic facades. Grasshopper parametric definition is used to bridge the gap between the early design stage and the energy-performance of the building, in terms of daylighting. The proposed design tool adds to the current performance-based technology by making particular contribution to the field of integrating energy-performance into the early design phase. The contribution includes finding the best-possible skin configuration for better daylighting performance on any day of the year.

Within the framework of this thesis, the performance of daylighting inside office spaces is studied through the use of new simulation tools that are capable of handling multi-inputs, as well as considering more than one variable at a time. The use of such tools allows not only for accurate results, but also almost instant variation of daylight performance when façade elements actuate. The complexity of this study lies in defining the intelligence of the skin, and simulating data exchange between multi-sensor layers, management system, and façade elements. A simple example was developed to see if the performance criteria could be achieved using Rhino as a modeling tool, Grasshopper as a parametric interface, DIVA 1.1 for daylight evaluation, and Galapagos for problem solving.

Rhino (http://www.rhino3d.com) is a 3d NURB-based modeling program. Until relatively recently, it has not been easily used in conjunction with simulation software. Now DIVA-for-Rhino supports a series of performance evaluations including links to Radiance, Daysim, and Evalglare (Rheinhart et al., 2010).

Grasshopper (http://www.grasshopper3d.com) is a free, graphical algorithm editor tightly integrated with Rhino's 3d modeling tools. It is possible to integrate pseudo-environmental effects such as sun and wind to dynamically change form. Sun systems have also been developed for it to achieve accurate sun shadow simulations, and two-way connections with Ecotect have been demonstrated.

DIVA (http://www.diva-for-rhino.com) is a Rhino plugin that can be directly run from the Grasshopper interface using a pre-built definition provided by Harvard GSD (SD)[2]. This definition allows data exchange between DIVA and Rhino, and uses Rhino as an interface for showing the results and the visualization. DIVA uses the following third-party software:[81]

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[81] "DIVA for Rhino - Credits."

- Radiance;
- Evalglare;
- GenCumulativeSky;
- Daysim.

Galapagos is a genetic algorithm feature that is used for problem solving cases within Grasshopper. It creates an evolutionary generic loop that populates generations of possible solutions with random individuals based on the predefined criteria. The system couples similar possible solutions together and then finds a best fit solution, which may end up being a locally optimal solution in some cases. Galapagos is used in this study to find the best possible tilt angles of the louvers' configuration for certain times of the day. However, Galapagos is run using a pre-defined set of parameters, leaving only the calculation for this tool.

4.2. CONCEPTUAL IDEA

Intelligence in buildings has always been influenced by human intelligence. But since human intelligence has not been powerfully modeled in simulation tools yet, the integration of all of the above tools into one system – to be used for this study – may enable the simulation of abstracted characteristics of intelligent kinetic features. Figure 4-1 shows how these features can be rationalized and abstracted for a simple modeling process using parametric tools.

Grasshopper is responsible for setting the input parameters, according to the desired luminous environment conditions, and passing these to the daylighting simulation tool, DIVA/Radiance, which then processes the data and sends the results back to Grasshopper for evaluation.

Grasshopper compares the results against the pre-defined performance criteria. If the results are acceptable, Grasshopper provides the generated solution as the best possible under the defined simulation conditions. If the results do not match the criteria, Grasshopper sets another scenario for the skin and triggers the simulation tool to re-run the new scenario and generate an outcome, and so on until an acceptable result is achieved (Figure 4-1).

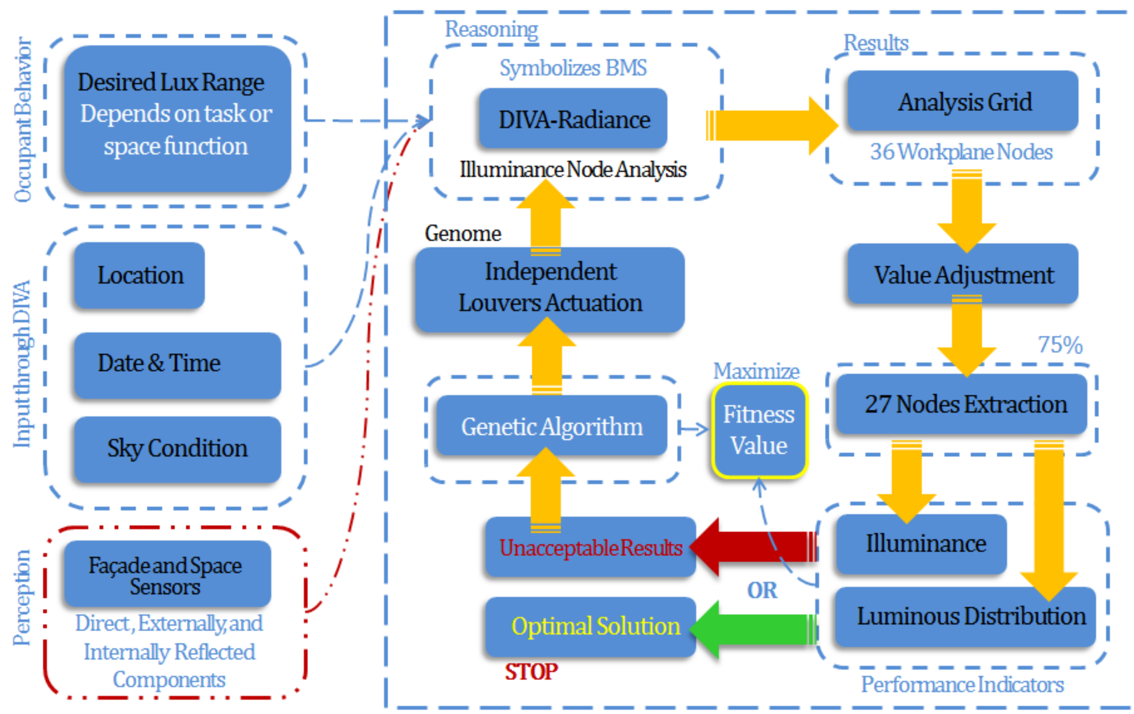

Figure 4-1: System logic – the path of data exchange between the proposed algorithm and the daylighting simulation tool.

The modeled space in Rhino has dimensions of 6.0m width, 7.5m depth, and fully-glazed height of 3.0m (Figure 4-2). The interior surfaces have been assigned reflectance of 80% for ceiling, 50% for walls, and 20% for floor. The secondary skin louvers have reflectance of 90%. The opening has been assigned generic doubled-glazed material with 72% visual transmittance.

Because of its sunny weather and daylight availability, Los Angeles has been chosen to be the location of the test and this south-facing office space.

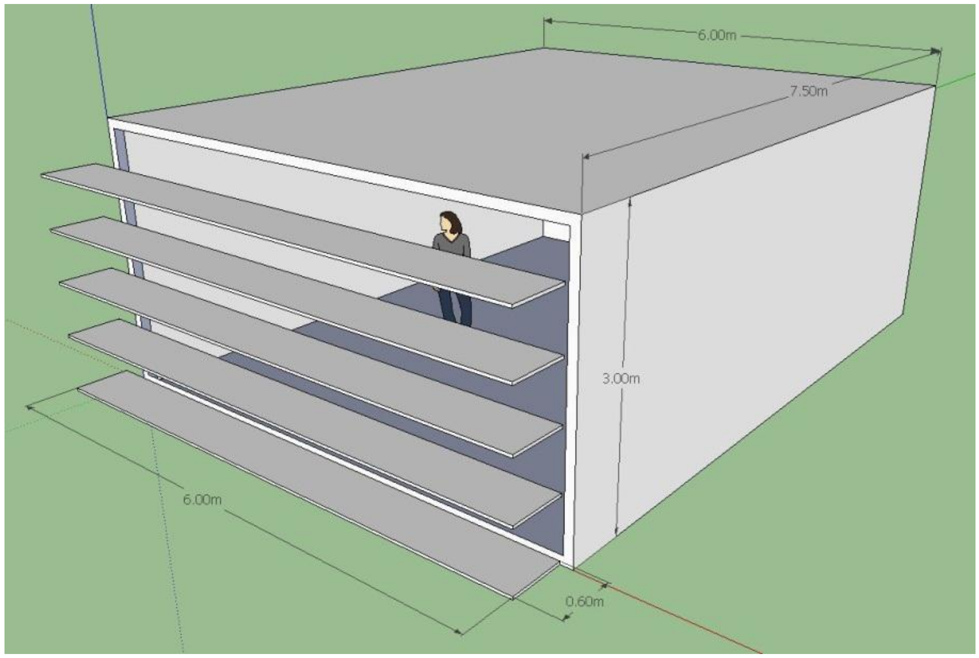

Figure 4-2: Space dimension - the dimensions of the office space used in the simulation.

Initially, the skin system is divided into 8 louver levels, where each level has two louvers (Figure 4-3). It is intended to control each of the ten louvers independently with different tilt angles. Though the system simulates daylighting according to the actuation of eight louvers, only five louvers cover the glazing portion of the space. These five louvers have the greatest impact on the luminous quality of the workplane. Figure 4-3 shows the algorithm for simulating 10 independent louvers based on five levels. However, for better presentation of the proposed design tool, each two louvers on the same level are treated with the same rotation angle, using another algorithm that will be shown later (Figure 4-4). This approach does not eliminate the flexibility of the definition to independently actuate each louver.

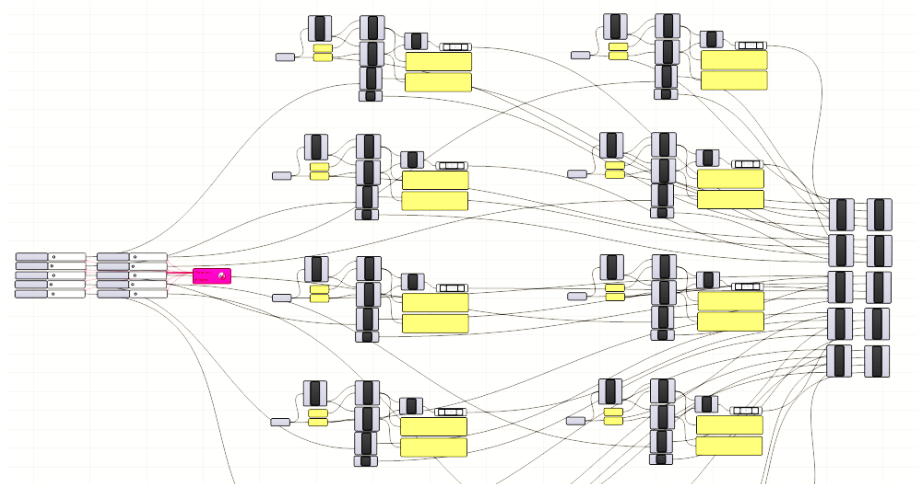

Figure 4-3: Louvers definition - part of the Grasshopper definition that illustrates the ten louvers with the angle sliders on the left hand side.

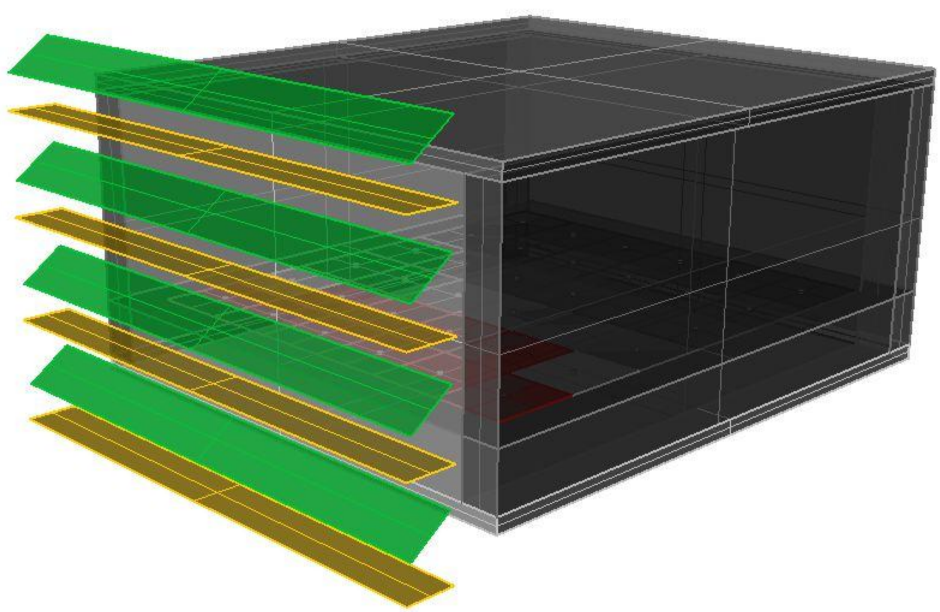

Figure 4-4: Independent split system - the two independent layers of louvers used in the proposed algorithmic design tool.

4.3. DESIGN TOOL DOCUMENTATION

This section documents the proposed design algorithm that can be used to determine an optimal configuration for the building skin for better daylighting performance. The algorithm is applied to a secondary skin configuration composed of horizontal louvers split into two independent layers. The definition utilizes Radiance as the calculation engine for daylighting. The definition has been divided into screenshots which are shown in this section. Each screenshot describes one part of the definition.

4.3.1 SKIN SYSTEM

This section of the definition has two similar parts, each of which operates one layer of louvers. The design of the secondary skin basically originated in Rhino, from a simple pair of rectangular louvers. Each louver was assigned as a "BRep" component to one of the definitions shown in Figure 4-5, and was duplicated using "move" components in Grasshopper. Prior to louver duplication, the geometry was exploded to define the vertices of the louver. Then, a midpoint was defined on the shorter edge of the louver and was set as the louver center of rotation.

The selected variables for the skin alteration are the rotation angle of the louvers and the distance between them. The rotation angle was set to a range of 0^{o} to 180^{o}, where 0^{o} to 90^{o} allows for a shading configuration of the louvers, and 90^{o} to 180^{o} allows for a harvesting position. The distance between the louvers ranges from 0.50m to 2.00m, where 0.50m allows for 0.12m overlap of two louvers, if required under certain circumstances, while 2.00m provides more potential for greater light penetration and better view of the outdoor environment, for certain overcast sky conditions.

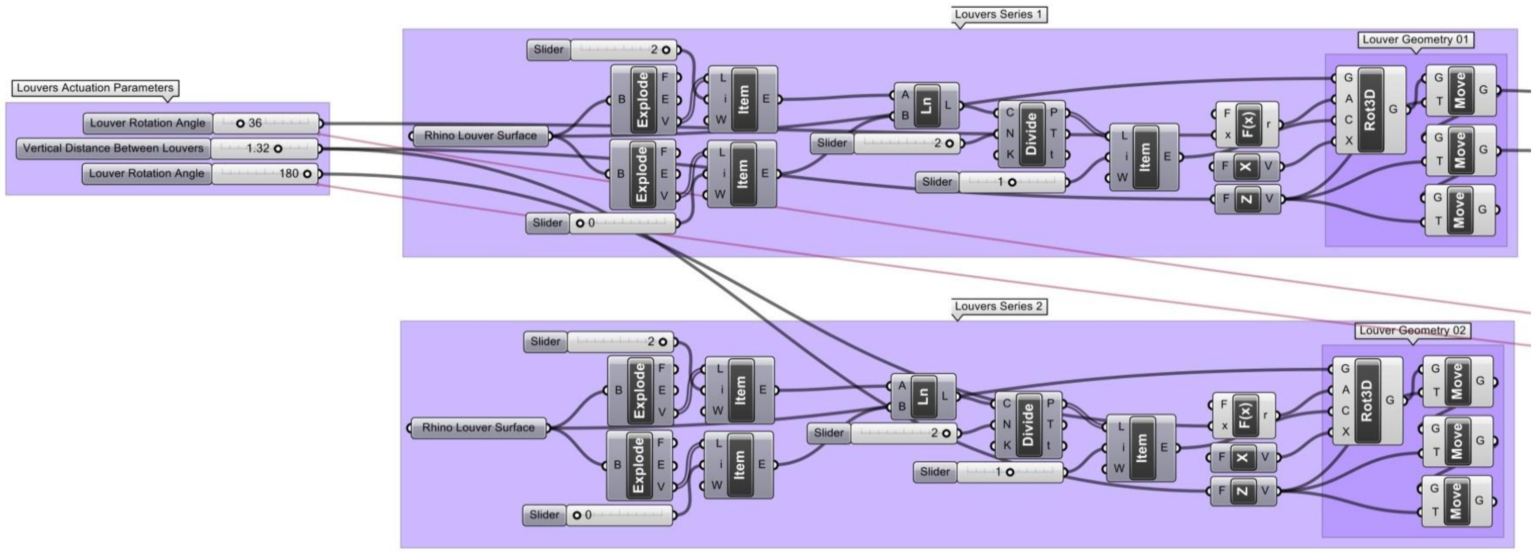

Figure 4-5: Independent louver actuation - the two independent layers of louvers used in the proposed algorithmic design tool.

Figure 4-6: Illuminance Scale - the desired illuminance scale based on the color swatch in the definition

Though only two variables were chosen for altering the skin for the purpose of this thesis, the algorithm has the potential to accept more variables, as well as to replace the original ones with new attributes. All that is needed is to replace this part of the definition by the new skin variables.

4.3.2 DIVA COMPONENT

This plugin component runs Daysim, the calculation interface, which employs a commonly-used calculation engine, Radiance. The DIVA version used in the algorithm is version 1.1. The component requires some inputs to get it properly running, among which are toggle run, metric input indicating the type of desired test, a slider that controls the kinetic elements, the geometry of moveable objects, and the material of the objects. The variant input refers to the name assigned to every simulation run; the component saves the results under this filename. As shown in Figure 4-7, the material assigned for the external louvers is high reflectance (90%).

On the right-hand side of the DIVA component, there are two different parts: visual adjustment for the illuminance, and 36 values of illuminance of the calculation grid. The visual adjustment, shown in Figure 4-7, results in showing the illuminance scale (Figure 4-6) in the Rhino viewport and over the calculation plane. One color swatch refers to the illuminance scale, and the other refers to showing the color gradient over the workplane (Figure 4-7). As mentioned in Chapter 3, the design illuminance range, according to IES, is 30-150 footcandles for office spaces.

4.3.3 ILLUMINANCE VALUES

The output from DIVA is viewed in a “panel” component in the Grasshopper definition, as shown in Figure 4-8. Though in the Rhino viewport the results do not include decimal places, the component in Grasshopper gives results up to six decimal places. Consequently, an adjustment to the values was applied for better evaluation, and the results are shown to two decimal places. Also, values have been converted from lux to footcandles by dividing each value by 10. The resultant value is an approximation of the footcandle value.

4.3.4 EVALUATION AND PERFORMANCE CRITERIA

After extracting the results from DIVA into a "panel" component, an acceptable range of illuminance of 30-150 footcandles was set according to the IES recommendations[82] (see Chapter 3). The range components convert all acceptable values into "true", and unacceptable values into "false". As mentioned in Chapter 3, the algorithm evaluates the space for three criteria: 75% of the points should be within the desired illuminance range (30-150 fc.); the luminous distribution contrast ratio between highest and lowest points should not exceed 10[83]; and the penetration depth of daylighting into the space should be greater than twice the window height.

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[82] IES North America, *IESNA Lighting Handbook*.

[83] Ibid.

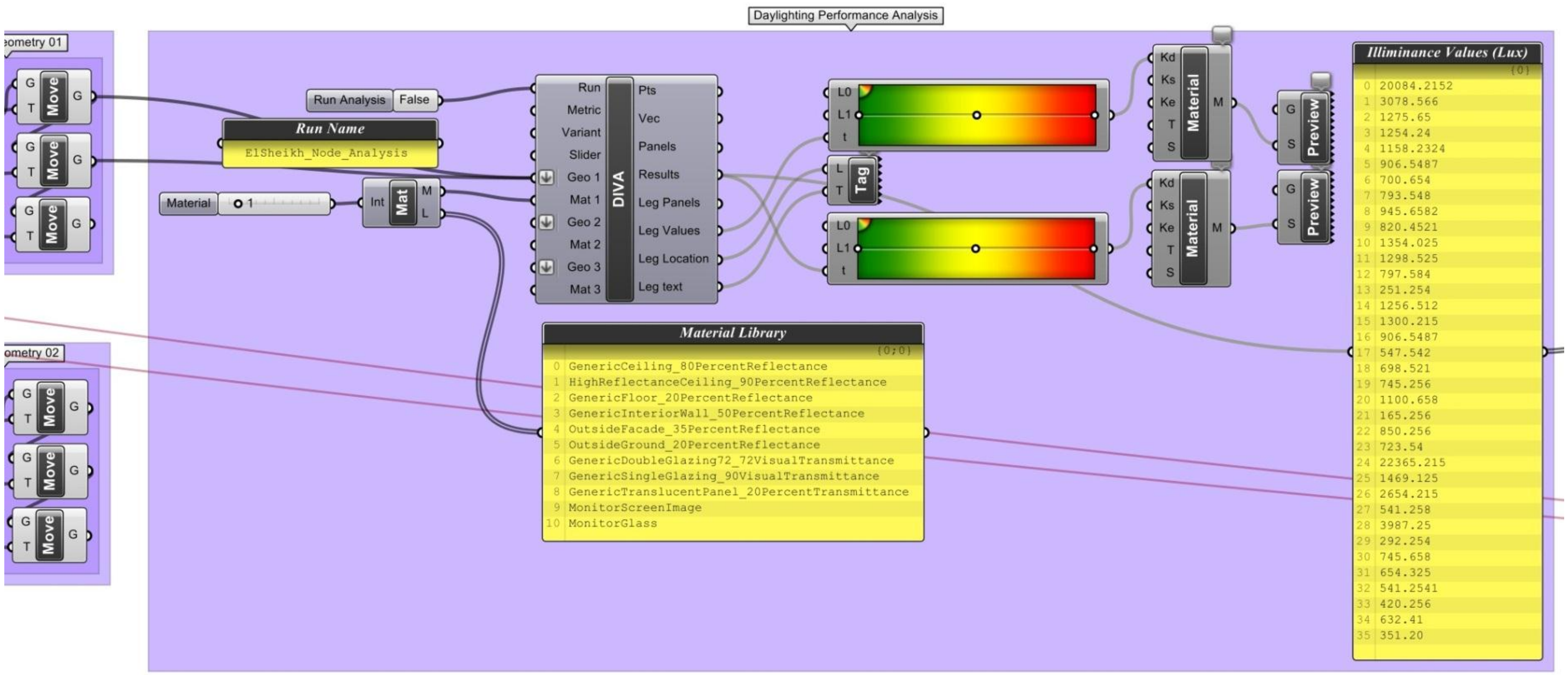

Figure 4-7: DIVA Component Section - the part of the definition responsible for running the analysis and extracting the results.

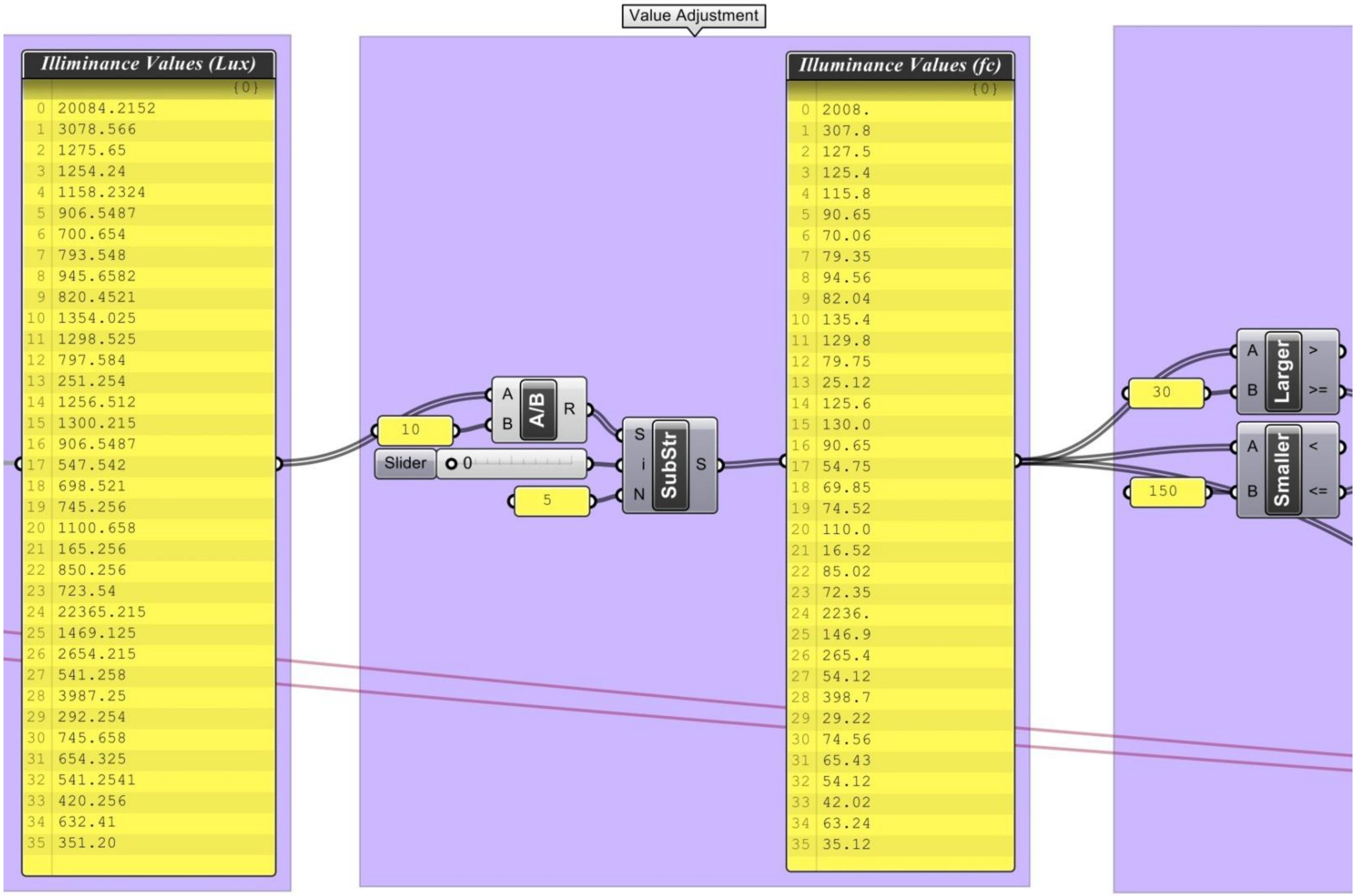

Figure 4-8: Value adjustment - the value adjustment prior to evaluation.

Using a "ReMap" component, all "true" and "false" values were converted into numbers: "1" for "true" and "0" for "false" (Figure 4-9). Then, these numerical values were sorted in descending order. According to the criteria previously set in Chapters 1 and 3, 75% of the 36 calculation points should fall within the range for acceptable luminous environment. Hence, the first 28 points should have a numerical value of "1".

As shown in Figure 4-10, a set of "list item" components were used to extract the values of 75% of the total points. These components extracted the items numbered "0" through "27", giving a total of 28 points. For an acceptable illuminance condition inside the space, the numerical value of 75% of the points should be "1", which means the sum of those points should be exactly "28". If the sum of the points was not equal to 28, the "panel" component would show "false", indicating an unacceptable illuminance condition inside the space (Figure 4-11).

The daylighting penetration depth criterion was indirectly included in the illuminance evaluation part. The simulation was based on a space depth of 2.5 x window height, 7.50m. Calculation points were evenly distributed all over the space, at a distance greater than twice the window height. Thus, these points were included in the 36 calculation points that were extracted from DIVA. If the final result showed "true", it meant that 75% of the space – which is greater than twice the window height – fell within the acceptable range.

The third and last performance indicator was the luminous distribution of daylighting inside the space, which, within the context of this study, is sometimes referred to as "contrast ratio". The IES recommends a contrast ratio between the lowest and highest illuminance values that does not exceed 1:10. Since the illuminance values were sorted in descending order, the highest value would have “0” index and the lowest value would have “35” index. These values were extracted using the “list item” component and divided by each other. If the resultant was between 1 and 10, the results were acceptable (Figure 4-12).

Adding to the efficacy of the experiment, a genetic algorithm was incorporated into the definition to enable a search for the best skin configuration at specific dates and times, or under different sky conditions. The genetic algorithm works on finding an optimal – but not necessarily the best – solution under certain parameters and conditions. These parameters could range from users’ desired illumination levels to externally-reflected daylighting components. Changes in any of these parameters triggered the system to run and find an optimal configuration for the skin to maintain the desired luminous environment.

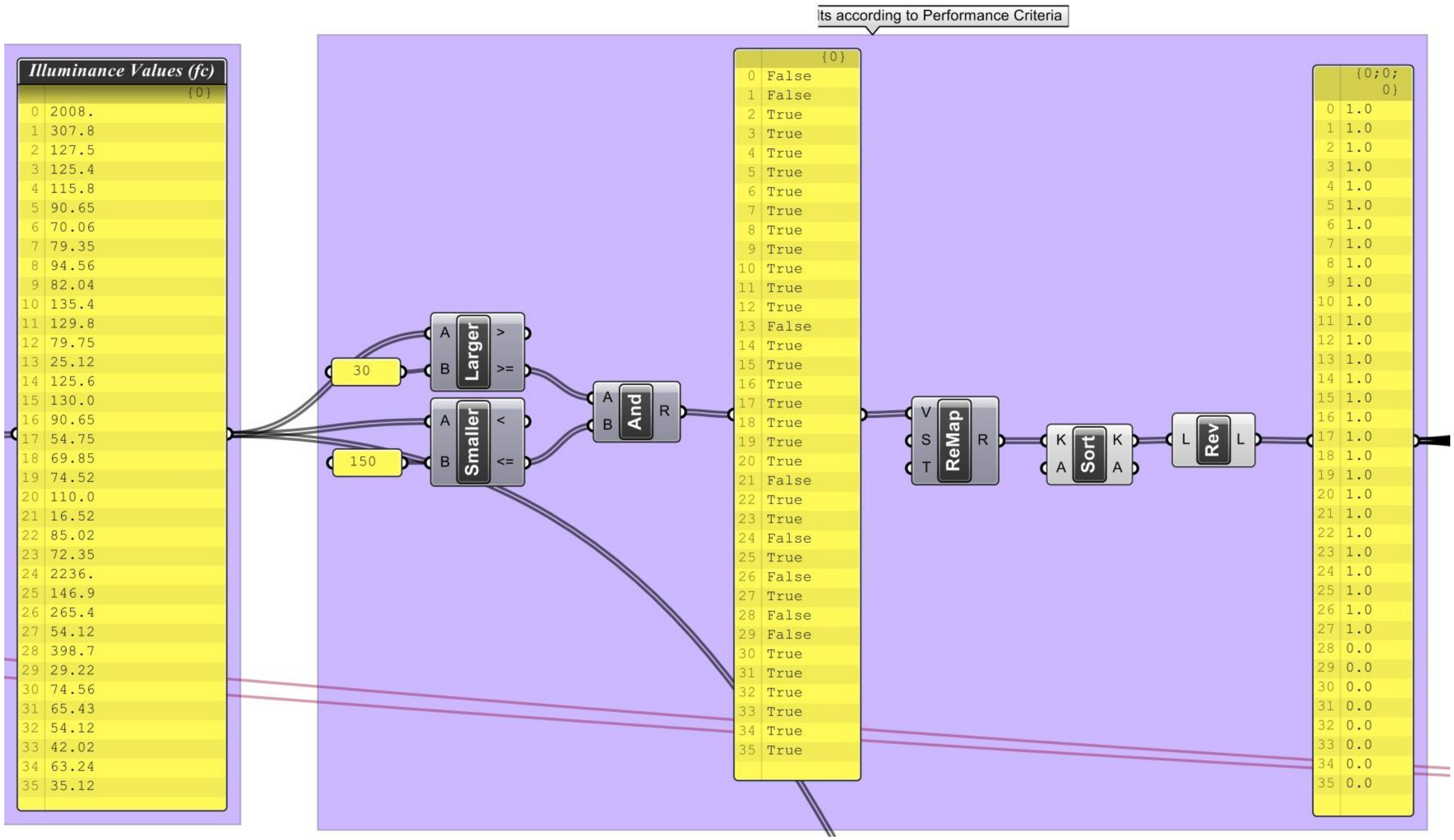

Figure 4-9: Illuminance values adjustment - converting illuminance values to “0” and “1” according to the acceptable range.

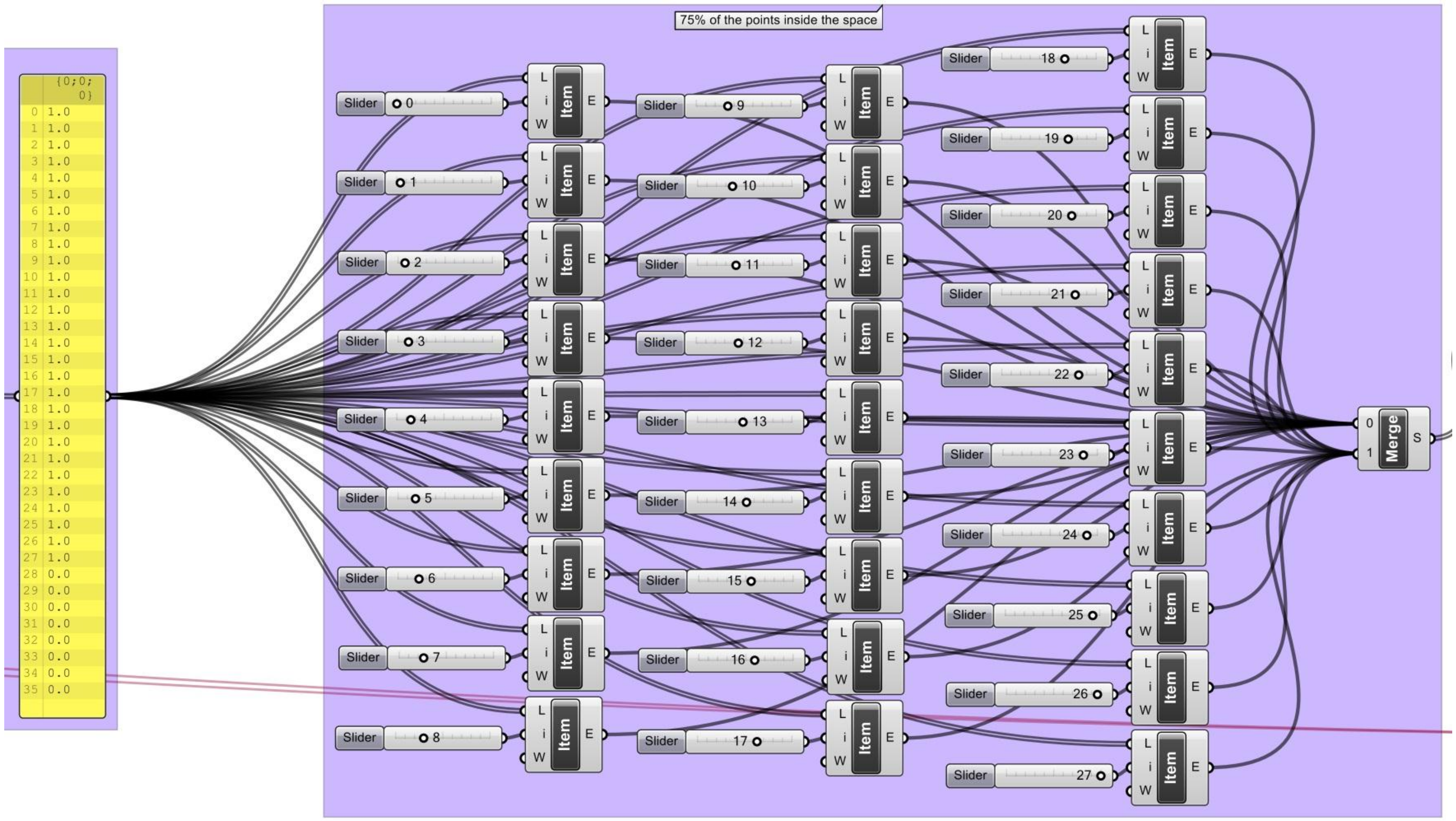

Figure 4-10: Calculation points extraction - extracting 75% of the calculation points for evaluation.

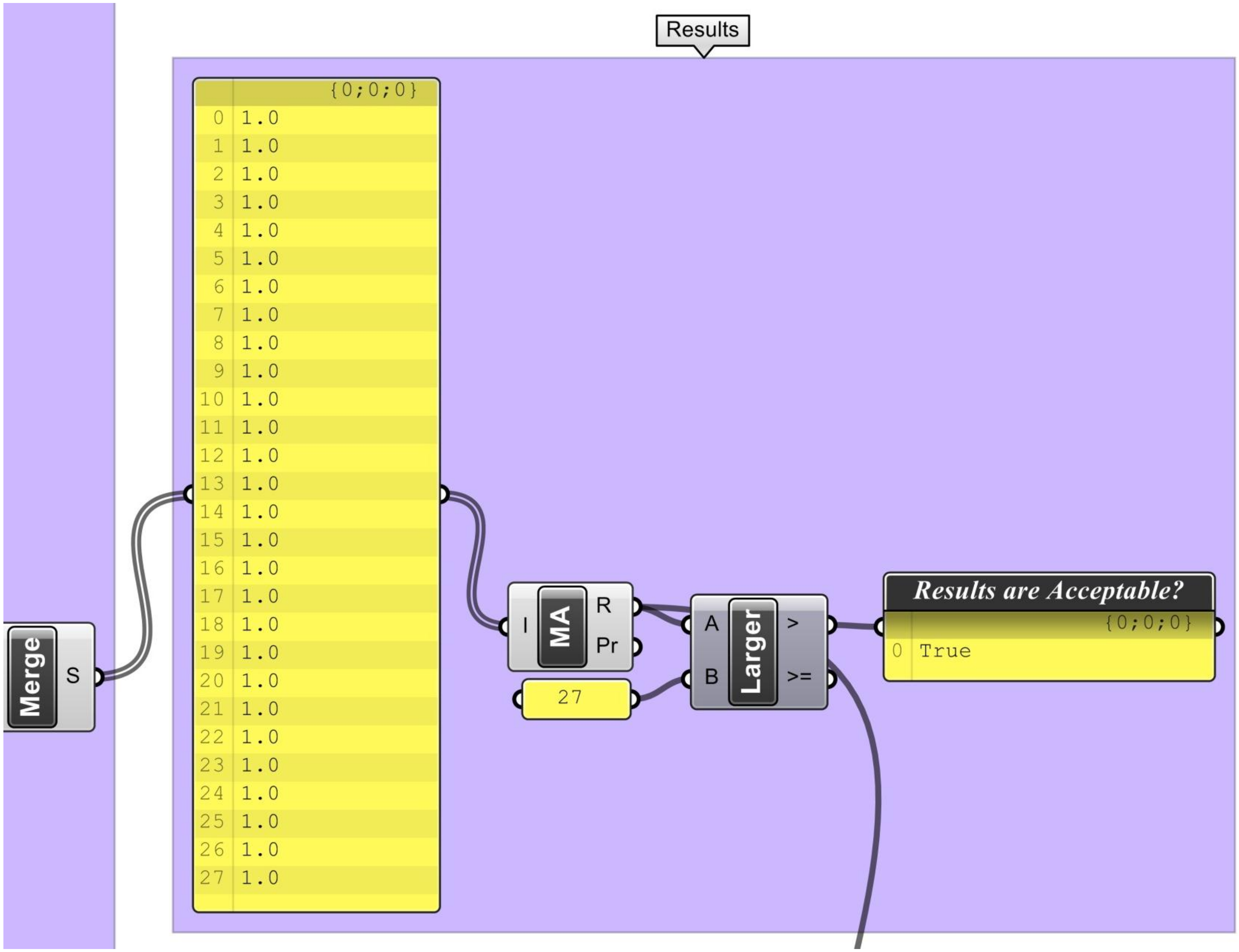

Figure 4-11: Illuminance evaluation result - the final result of the illuminance performance criteria

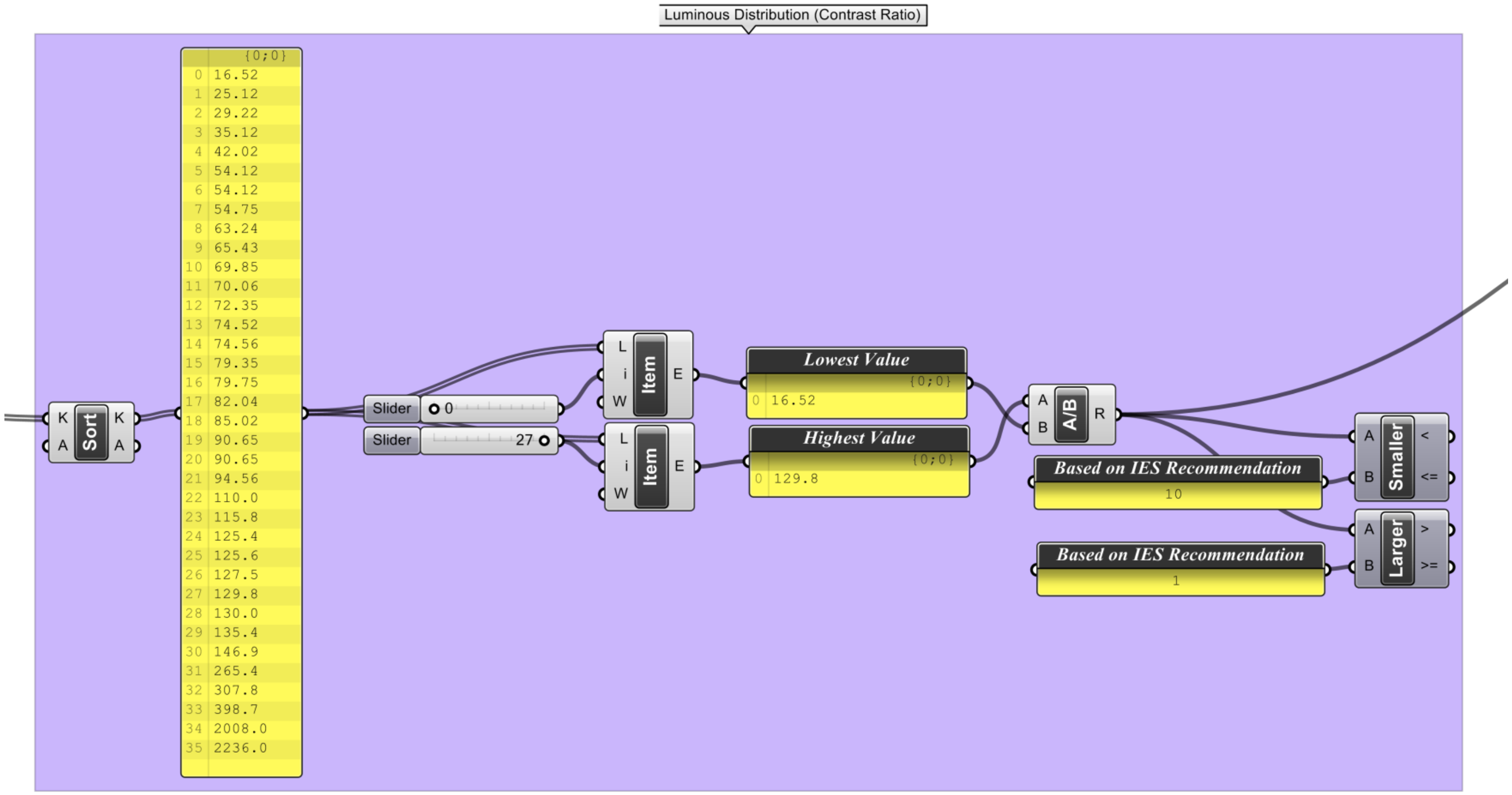

Figure 4-12: Luminous distribution evaluation criteria - the components designed to evaluate the luminous distribution inside the space.

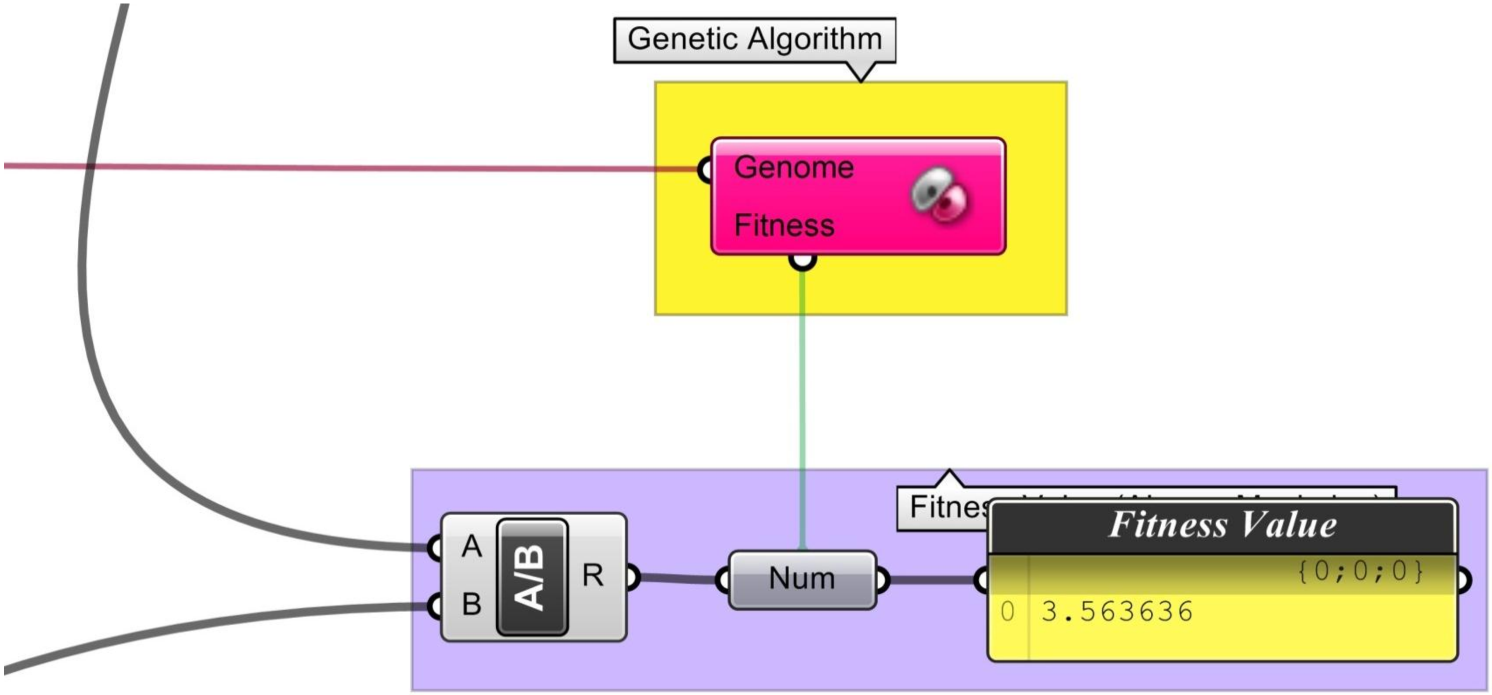

Figure 4-13: Genetic algorithm fitness value - the genetic algorithm component connected the fitness value.

As a final procedure, Galapagos was added to the definition to search for an optimal configuration of the louvers that achieved the main three performance criteria previously mentioned. It creates an evolutionary loop that populates generations of possible solutions with random individuals based on the previously defined criteria. The system couples similar possible solutions together and then finds a best fit solution. This might end up being a locally optimal solution in some cases, but Galapagos should at least find a good solution if it exists, even though it might not be the best possible solution. As shown in Figure 4-13, Galapagos was connected to three variables of the louver system. However, the main alteration primarily explored is the independent louver tilt angle.

This definition is intended to be used as a design tool for exploring various skin configurations and testing them against daylighting performance. Despite the simplified algorithm, data processing passes through performance criteria for numerical evaluation. Also, the complexity of the definition is in its openness to the addition of more layers, such as more rotation sliders, geometry alteration, or more evaluation criteria for different daylight performance indicators.

Though the algorithm is complete, it has not been run for testing, due to technical problems with the DIVA component. According to the developers, DIVA 1.1 does not allow writing nodes data for illuminance and showing it in Grasshopper. This limitation puts the success of the design tool in a "pending" status until the release of a modified version of DIVA which has this problem fixed; the release date was unknown when writing this thesis. However, to fully illustrate the idea and concept, Chapter 5 shows some manual simulations for various skin configurations and their impact on daylighting performance inside the space. For certain dates and times, a series of skin configuration is selected to show the pattern of actuation over the course of a day for enhanced luminous environment.

5. CHAPTER 5 **DAYLIGHTING SIMULATION METHOD**

Due to technical difficulties experienced with testing the algorithmic design tool, manual simulation for some skin configurations is presented in this chapter. The chapter provides various scenarios for the louver configurations for select times of the year. Finally, a scenario for a specific day is compiled to show how an intelligent-dynamic louver system would actuate in response to changing conditions.

5.1. OVERVIEW

After finishing the algorithm, which was intended to test an intelligent dynamic louver system for daylight harvesting performance, the simulation run was not successful due to some technical difficulties with the DIVA 1.1 component scripting, which does not allow extracting illuminance node values from DIVA/Rhino. This problem made it difficult to provide node values for evaluation, which consequently eliminated the possibility of running Galapagos to find an optimal solution for skin configuration for a specific time of the year.

Instead of only documenting the parametric algorithm (Chapter 4), it is useful to manually simulate some louver configurations, analyse the results, and compile one scenario for a kinetic louver system on a certain day of the year. The objective of this study is to provide measured illuminances based on direct and diffuse outdoor illumination under different sky conditions and numerous settings of the secondary skin of the kinetic louver system. For this manual run, some variables have been set constant, which contradicts the approach of the algorithm to automatically run numerous probabilities for the skin configuration under various conditions. The same design conditions assumed in the algorithm were used for the manual runs.

5.2. SIMULATION CONDITIONS

5.2.1 LOCATION, DATE & TIME

Los Angeles, California, was set as the location for the simulation, based on its high ranking in the list of American cities with most sunny days. Los Angeles is number 10, with 186[84] sunny days annually; this is approximately 51% of the whole year. This number is an average based on readings over 30 years.

Los Angeles is at latitude 34.05⁰ N (Figure 5-1) and longitude 118.25⁰ W. The solar altitude changes at different times of the day, and throughout the year; it ranges from 12⁰ to 83⁰ for the selected test times. Figure 5-2 shows the solar altitude at different times of the day on June 21st, March-September 21st, and December 21st (the summer solstice, equinox, and winter solstice, respectively). The solar times chosen for this simulation were 9am and 12pm, when changing solar altitude takes place. Though the altitude changes after 12pm, the afternoon times were not considered because they show a mirroring of the morning altitudes (Figure 5-1). The simulation was run twice for each date and time, once with a clear sky, and once with an overcast sky, to test the performance of the dynamic louver system under different sky conditions.

The office space used in this study is assumed to be in a high-rise building, and on an upper floor, where no ground reflectance exists. While a proper simulation model should take into

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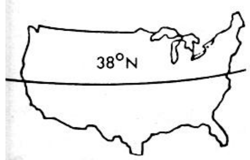
[84] "Weather Today - Weather Forecasts, Radar, Maps for 1000s of US and World Cities."

account the surrounding context, this model does not account for neighboring buildings. Hence, only indirect illumination from the space and the louvers is considered.



Latitude		Date	Solar Time* AM: 6 PM: 6	AM: 7 PM: 5	AM: 8 PM: 4	AM: 9 PM: 3	AM: 10 PM: 2	AM: 11 PM: 1	Noon
30°N	ALTITUDE	June 21	12	24	37	50	63	75	83
		Mar.–Sept. 21	—	13	26	38	49	57	60
		Dec. 21	—	—	12	21	29	35	37
	AZIMUTH	June 21	111	104	99	92	84	67	0
		Mar.–Sept. 21		83	74	64	49	28	0
		Dec. 21	—		54	44	32	17	0
34°N	ALTITUDE	June 21	13	25	37	50	62	74	79
		Mar.–Sept. 21	—	12	25	36	46	53	56
		Dec. 21	—	—	9	18	26	31	33
	AZIMUTH	June 21	110	103	95	90	78	58	0
		Mar.–Sept. 21		82	72	61	46	26	0
		Dec. 21	—	—	54	43	30	16	0
38°N	ALTITUDE	June 21	14	26	37	49	61	71	75
		Mar.–Sept. 21	—	12	23	34	43	50	52
		Dec. 21	—	—	7	16	23	27	28
	AZIMUTH	June 21	109	101	90	83	70	46	0
		Mar.–Sept. 21		81	71	58	43	24	0
		Dec. 21	—	—	54	43	30	16	0

Figure 5-1: Space dimensions - the dimensions of the space used in the simulation.[85]

5.2.2 SPACE DIMENSIONS & MATERIALS

A space 6.00m wide, 7.50m deep, and 3.00m high was modeled for this study (Figure 5-2). The louvers are 0.60m deep, 6.00m wide, and set 1.00m from the glazing, to allow for a catwalk. The distance between the louvers was set to 1.30m, which allows partial overlapping in nearly closed shading/harvesting conditions. The depth of the space goes beyond the traditional distance of twice the window height, which is one of the performance criteria, as previously

[85] Schiler, *Simplified Design of Building Lighting*, 97.

mentioned in Chapter 3. The calculation grid was placed at 0.70m from finish floor level. Material selection was based on basic generic materials provided by DIVA. Floors, walls, ceiling, and louvers were assigned reflectances of 20%, 50%, 80%, and 80%, respectively (Figure 5-3).

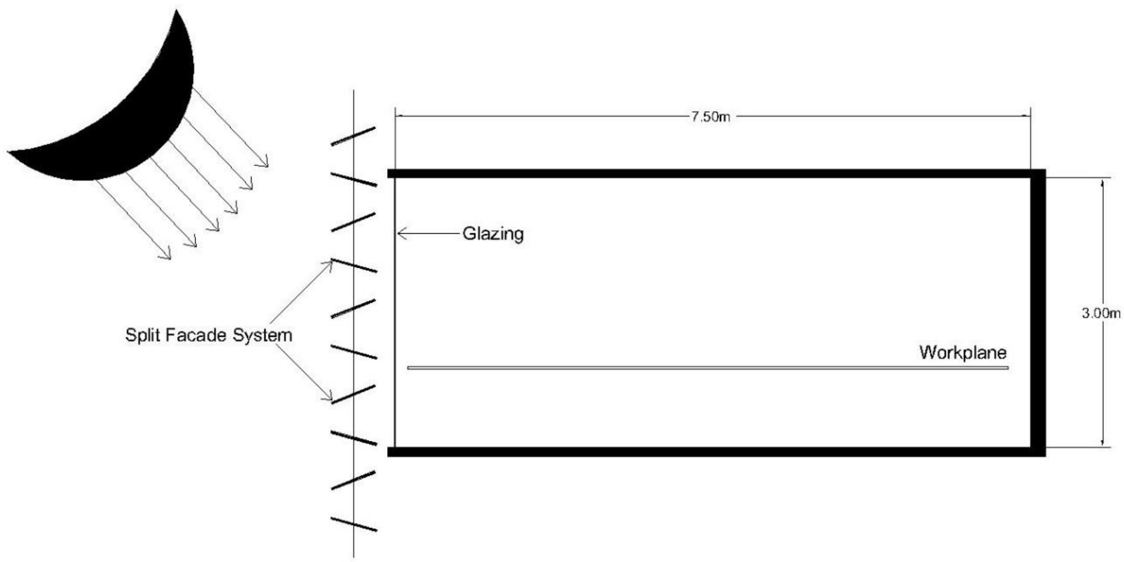


Figure 5-2: Modeled Space - conceptual image of the space and its dimensions.

Figure 5-3: Materials selection - a snapshot of the “assign materials” window in DIVA for Rhino.

5.2.3 RADIANCE SETTINGS

DIVA for Rhino has a user-friendly interface, which one uses to choose the type of lighting test, sky condition, solar date and time, and desired illuminance range. Within the context of this study, the “lighting test” was set to “illuminance values,” for the calculation of illuminance nodes evenly distributed over the working plane. The sky condition was set to either “sunny CIE clear sky with sun” or “cloudy CIE overcast sky” (Figure 5-4). Solar dates and times used in the study were June 21st at 9:00am (06 21 09), June 21st at 12:00pm (06 21 12), Dec 21st at 9:00am (12 21 09), Dec 21st at 12:00pm (12 21 12), March 21st at 9:00am (03 21 09), and March 21st at

12:00pm (03 21 12). The range of desired illuminance was set to 300-1500[86] lux, according to the IES recommended range for office spaces. Any value smaller than 300 lux or greater than 1500 lux was highlighted in the simulation results in the form of a percentage.

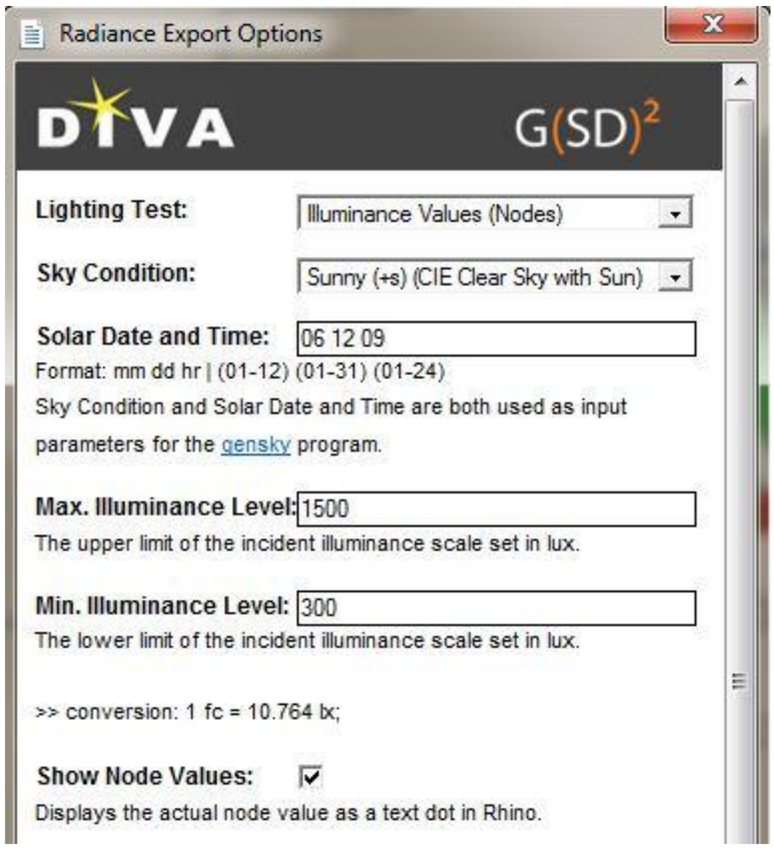


Figure 5-4: Simulation parameters - the settings used for the simulations.

The same advanced radiance parameters were used for all simulation runs. These parameters assertively impact the accuracy and simulation time of raytracing calculations. Figure 5-5 shows the radiance parameters used for the study. “Ambient bounces” represents the number of

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[86] Bradshaw, *The Building Environment*, 259.

diffuse bounces computed by the indirect calculation. A value of zero implies no indirect calculation.[87] Though it consumes more time for calculation, a value of 5 ambient bounces was used, which denotes the consideration of the maximum amount of indirect calculation.

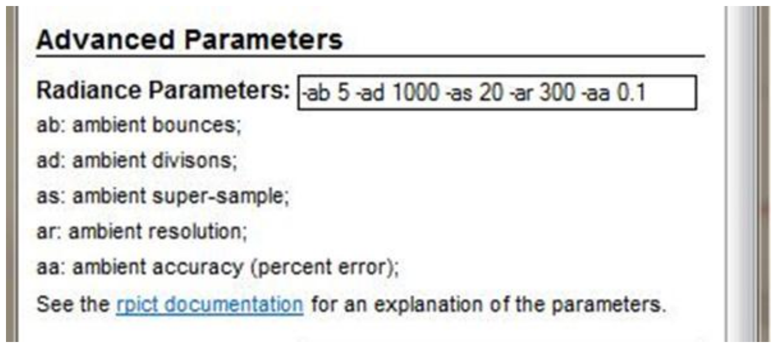

Figure 5-5: Radiance parameters - the settings used for "Radiance" parameters.

5.3. SIMULATION METHOD

There are infinite possibilities for the combined skin configuration of the intelligent-kinetic louver system, since the proposed system depends on independent angle control, where each louver may have its own tilt angle. Therefore, the best approach for this study is to use parametric software that automatically generates as many possibilities as the designer desires. But for manual simulation, it is extremely time consuming to adjust each louver to a specific tilt angle. Accordingly, some skin configurations have been defined based on previous research in the field.

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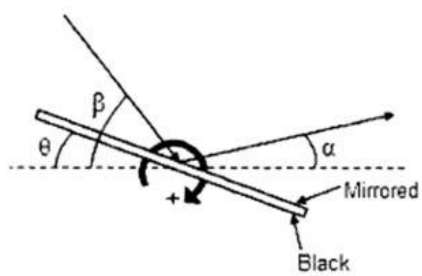
[87] "Radiance rpict program."

In 2005, Molly McGuire explored the independent blind angle control for venetian blinds, and its impact on ceiling illuminance[88]. Using a physical modeling approach, she was able to establish conclusions for light-reflection on the upper surface of venetian blinds. In her research, she presented three equations for three variables: incident angle, reflected angle, and blind tilt-angle. These equations are useful in determining the reflected angle, which consequently gives hints about where the light is going into the space (Figures 5-6 and 5-7). The first equation in Figure 5-6 gives the redirected (exit) angle as a function of the depth of the space and the height of the window. The second equation in the same figure expresses the redirected angle as a function of incident solar angle and louver tilt angle.



$$\alpha = 90^\circ - \arctan\left(\frac{d}{h}\right)$$

$$\alpha = \beta + 2\theta$$

β Incident Solar Angle
θ Louver Angle
α Redirected Angle
d Room Depth
h Window Height

Figure 5-6: Redirected angle for single configuration - the equations by Molly McGuire for redirected angle calculation for systems with either harvesting or shading setting.[89]

For example, if daylighting is necessary at a depth of 10.00m in a space which has a window opening of height 3.20m, using the first equation in Figure 5-6, the desired redirected angle "α" of the rays is 17.70°. By substituting this value in the second equation, assuming the incident

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[88] McGuire, "A system for optimizing interior daylight distribution..."

[89] Ibid.

solar angle is 62^{o} in June at 10:00am, the louver tilt angle should be -22.15^{o}. This angle is measured from the horizontal reference guide counterclockwise (from the right hand side), and this explains the negative sign that refers to the shading position.

$$\cos(\alpha) = \frac{1}{2}\left[\sin(|\theta_s - \beta|) + \sin(|\theta_R - \beta|)\right]$$

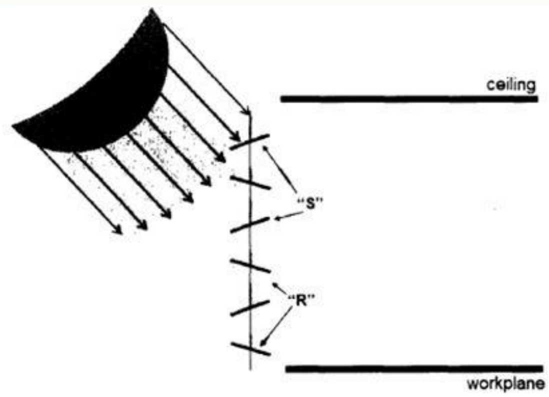

Figure 5-7: Redirected angle for combined configuration - the equations by Molly McGuire for redirected angle calculation for systems with harvesting and shading settings.[90]

For the purposes of this thesis, the value of "θ" was revised, as shown in Figure 5-8, to measure the angle from the indoor side of the horizontal plane to the tilted louver counterclockwise. This makes it easier to differentiate between shading and harvesting positions, where shading position angles range from 0^{o} to 90^{o}, and harvesting position angles range from 90^{o} to 180^{o} (Figure 5-8).

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[90] Ibid.

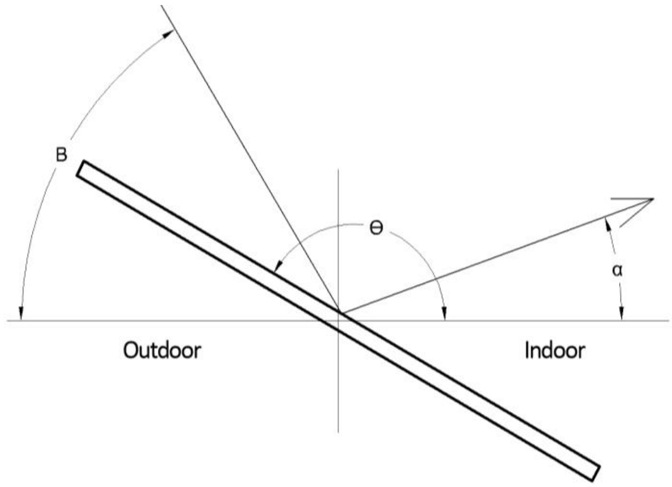

Figure 5-8: Revised angles diagram - the revised value of "ϴ" which is used in this study.

Within the framework of this study, eight louvers in a secondary skin layer were placed at a distance of 1.00m in front of the glazing, which is a typical distance for a catwalk. These louvers were split into two independent layers of actuation, as shown in Figure 5-9.

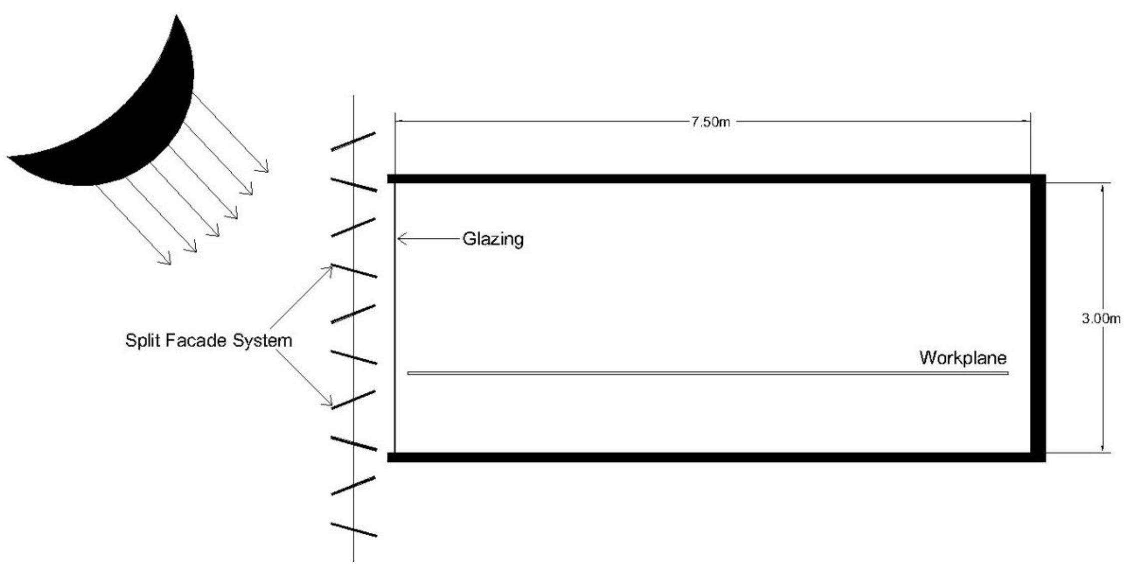

Figure 5-9: Louver Configuration - the actual space used in the study with split louver system as a secondary skin.

The distance between the louvers was set to 1.30m, to allow for partial overlapping in semi-closed positions. Overlapping at high-tilt angles ensures multi-surface light deflection, where light is bounced off the upper surface of the louver, hits the lower surface of the upper louver, and exits into the space. This phenomenon occurs at any tilt angle, but does not work with high-tilt angles with no overlapping distance.

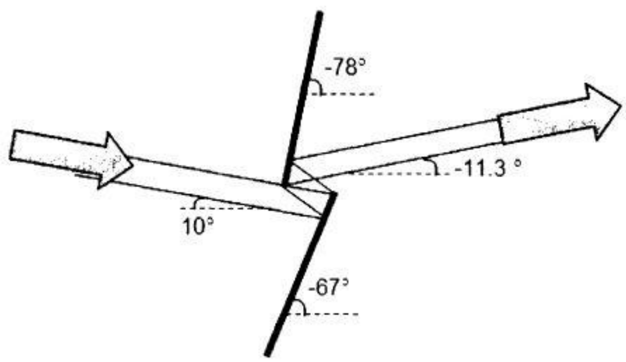

Figure 5-10: Semi-closed condition - partial overlapping in semi-closed condition.[91]

In her research, McGuire generated a table of angles of combined schemes of harvesting and shading, for different incident solar angles. The table shows the optimal configurations for incident solar angles ranging from 10° to 80° (Figure 5-11); the table applies to this study since solar angles experienced in Los Angeles range from 18° to 79°.

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[91] Ibid.

Table 3.1.2 Optimal configurations for incident solar angles ranging from 10° to 80° for shading/redirecting scheme

Incident Solar Angle	Optimal Angle: *R* Blinds[1]	Best Allowable Angle: *R* Blinds	*S* Blind Angle	% of Incident Radiation Redirected	Penetration Depth [m]
10° [2]	-1°	NA	NA	NA	NA
15°	2°	NA	NA	NA	NA
20°	4°	NA	NA	NA	NA
25°	7°	-30°	-65°	43%	0.17
30°	9°	-17°	-60°	40%	1.0
35°	12°	-5°	-55°	37%	2.0
40°	14°	7°	-50°	33%	4.1
45°	17°	17°	-26°	31%	10.3
50°	19°	19°	-2°	37%	9.4
55°	22°	22°	18°	45%	10.3
60°	24°	24°	24°	95% [3]	9.4
65°	27°	27°	27°	95%	10.3
70°	29°	29°	29°	95%	9.4
75°	32°	32°	32°	95%	10.3
80°	34°	34°	34°	95%	9.4

[1] All angles rounded to nearest degree.

[2] Not possible to redirect incident rays lower than 25° without allowing some directly transmitted light.

[3] The redirecting blind angle for incident rays 60° and greater provides sufficient shading, so all blinds may be set to the redirecting angle.

Figure 5-11: Optimal tilt angles - the optimal configuration for various solar angles.[92]

While McGuire's research identifies an optimal tilt angle for each solar altitude, each tilt angle combination selected for simulation in this study was run for three different altitudes, at 9:00am and 12:00pm, and under clear and overcast sky conditions, for June 21st, March 21st, and December 21st. Figure 5-12 shows a list of tilt angle combinations for the simulation runs. Each configuration, excluding the first three in the figure, is followed by two tilt angles, where each

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[92] Ibid.

represents the tilt angle of one layer of the system; one layer has every other louver at the same tilt angle. Three out of the thirteen configurations are used for referencing and comparative analysis; these cases are “glazing only”, “lightshelf”, and “horizontal louvers”. Then, a series of shading, harvesting and combined configurations were run and tested for daylighting harvesting and three main performance criteria, as previously mentioned in Chapter 3.

Skin Configuration	Angle	Notes
Glazing only	Not Applicable	Simulation run with glazing only.
Lightshelf	0^o	Simulation run with lightshelf only.
Horizontal Louvers	0^o	Simulation run with static horizontal louvers.
Shading	0^o, 45^o	Simulation run with louvers in shading configuration.
	10^o, 45^o	
	35^o, 55^o	
Harvesting	145^o, 160^o	Simulation run with louvers in harvesting configuration.
	153^o, 153^o	
Combined	24^o, 156^o	Simulation run with combined configuration of shading and harvesting.
	26^o, 163^o	
	55^o, 168^o	
	170^o, 10^o	
Top-Lower Split	26^o, 168^o	Simulation run with split configuration of harvesting for upper part and shading for lower part.

Figure 5-12: Simulation Cases - the various simulation tilt angles for the louver system.

Simulating each angle combination for two sky conditions and 6 different times, results in 156 figures, all of which can be located in Appendix A.

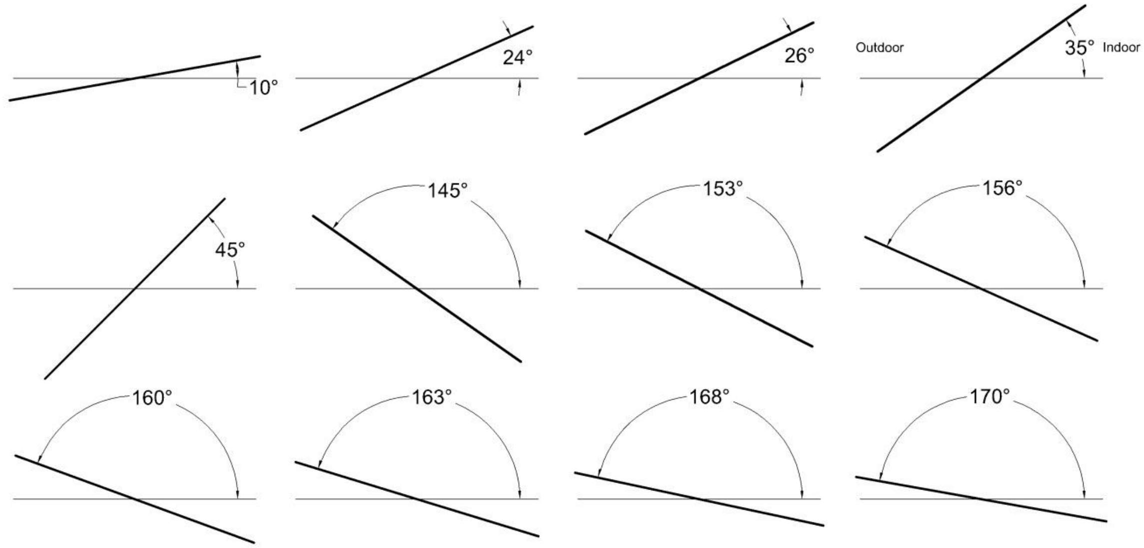

Figure 5-13: Visual presentation of tilt angles - all tilt angles used in the simulation.

5.4. UNDERSTANDING SIMULATION RESULTS

This section describes an illuminance node analysis sample. As shown in Figure 5-14, the space was divided into a 6x6 grid, resulting in 36 evaluation nodes. DIVA shows illuminance values in lux; dividing each value by approximately 10 gives the illuminance value in footcandles. The graphical scale shows a value range from 300 to 1500 lux, based on the performance criteria (see Chapter 3), where 300 lux is blue and gradually changes to become red, indicating 1500 lux. Also, this tool provides the “mean illuminance” of each run, which is calculated by adding together all values and dividing the result by 36, the total number of nodes enclosed by the space.

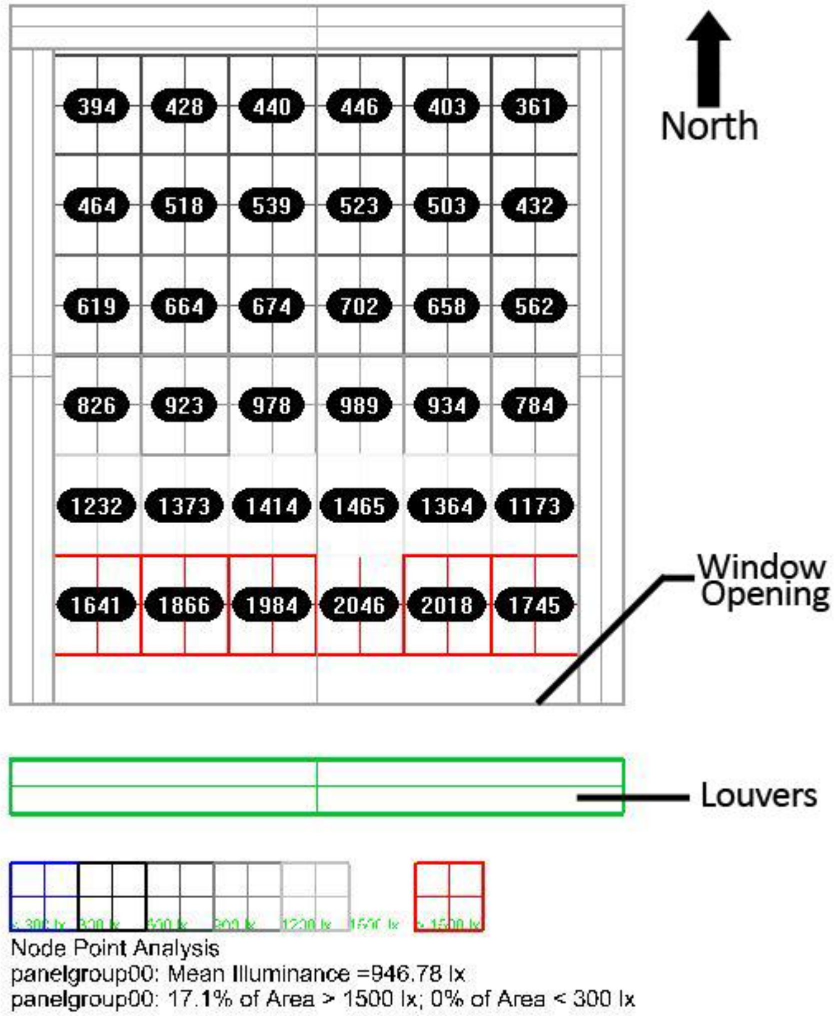

Figure 5-14: Illuminance nodes results sample - a typical output sample of DIVA node point analysis.

According to the performance criteria described in Chapter 3, an acceptable luminous environment requires at least 75% of the nodes to fall within the IES recommended illuminance range, 300-1500 lux[93]. Hence, an acceptable case should have no more than 25% of its area

[93] Bradshaw, *The Building Environment*, 259.

above 1500 lux or below 300 lux (Figure 5-14). However, the analysis was developed based on bringing the percentage of acceptable node-points as close as possible to 75%.

5.5. VISUALIZATION OF SIMULATED SCHEMES

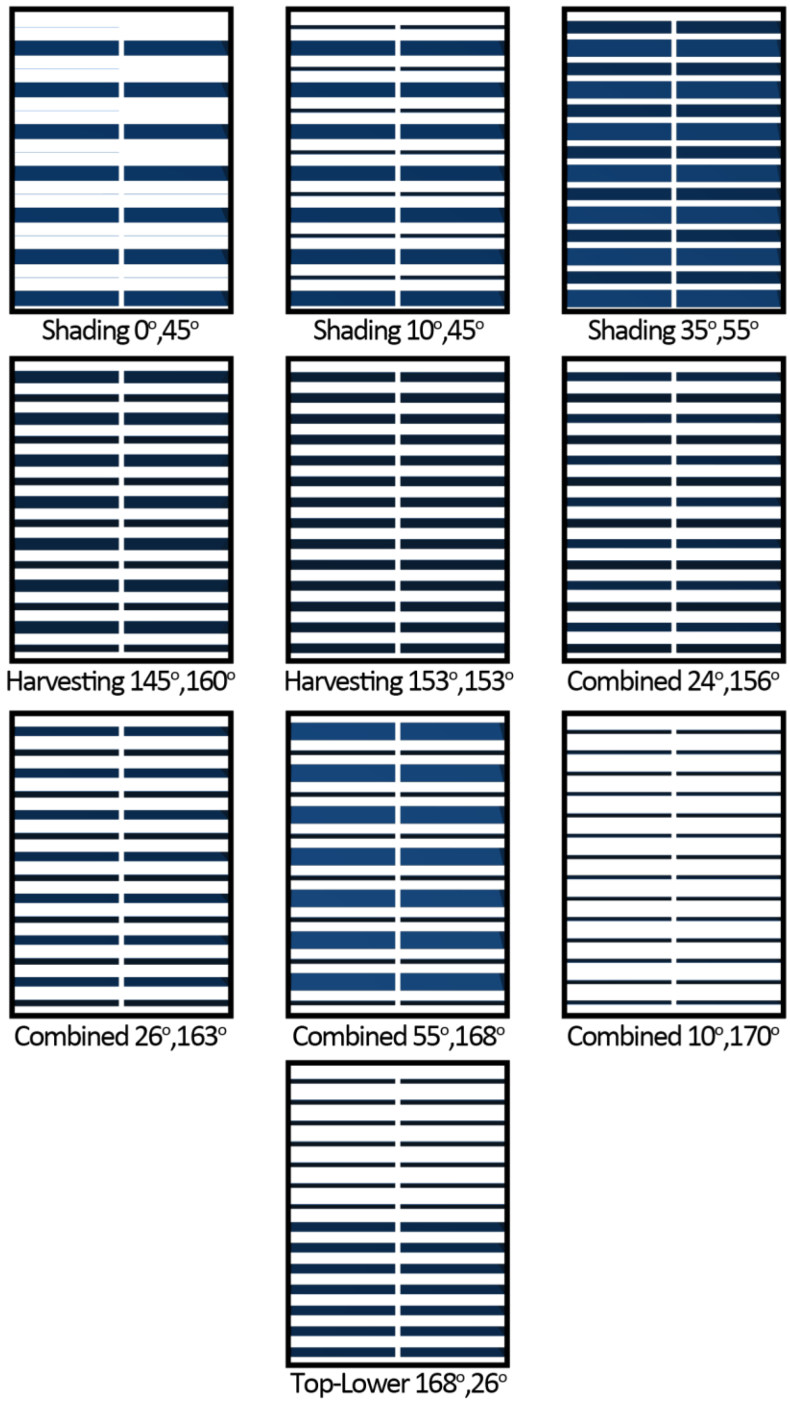

Figure 5-15: Front view of simulated schemes - a visualization of simulated schemes.

Figure 5-16: Perspective view of simulated schemes - a visualization of simulated schemes in the same order as previous figure.

6. CHAPTER 6 **SIMULATION ANALYSIS**

The actuation of external louvers influences the quality of the luminous environment inside the office space. Each combined configuration of the louver system impacts the quantity and quality of daylight. This chapter provides analysis of select case results that were generated by DIVA-in-Rhino, based on different secondary skin configurations.

In this study, assessment and analysis of secondary skin performance, in terms of daylighting, is based on illuminance values with which illumination, luminous distribution, and depth of penetration can be evaluated. Using DIVA-in-Rhino, 156 node-analysis diagrams (see Appendix A) were generated for different dates, times, and sky conditions. The results diagrams showed variation in the quality of the luminous indoor environment. Some cases showed interesting results which merit highlighting and analysis. This chapter discusses the data collected and the results of these select simulation cases, which were obtained by the method discussed in the previous chapter.

The various tilt angles simulated in this chapter include shading, harvesting, and combined configurations. The combined configuration, as previously mentioned, is a system where every other louver has different tilt angle. Figure 6-1 shows a graphical explanation of how the different angles are incorporated into a single façade system.

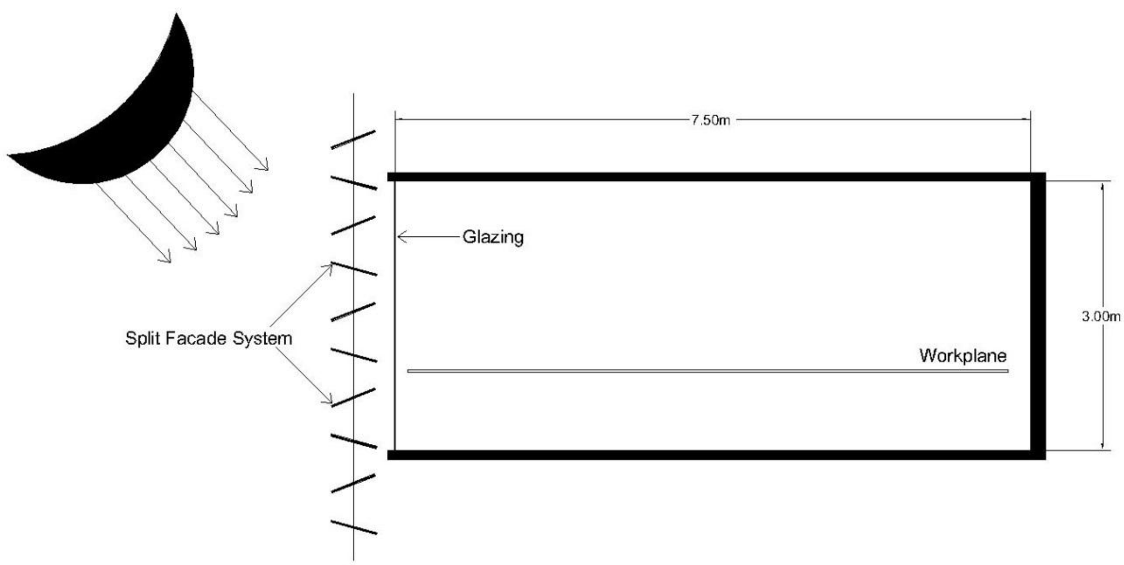

Figure 6-1: Independent tilt-angle system - incorporating two different angles into one façade system.

6.1. DATA ANALYSIS METHOD

6.1.1 DIAGRAMS AND CHARTS

Data analysis consists of evaluating the secondary louver skin layer for daylighting performance. As previously mentioned in Chapter 3, the evaluation method assesses the quality and quantity of daylight inside the office space in terms of illuminance variation, luminous distribution, and depth of daylight penetration. The method of analyzing and interpreting data involves quantitative evaluation of the behavior of daylight inside the space, using node analysis grids – generated by DIVA – and illuminance charts produced based on these grids. Results are presented by comparing the test case to the pre-defined performance criteria and two base cases for skin configuration, using lightshelf and horizontal louvers.

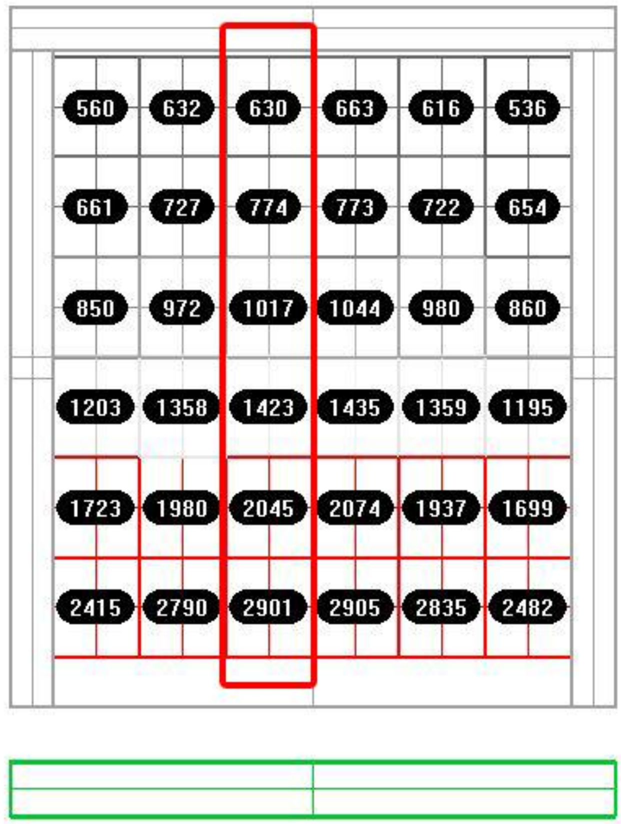

Figure 6-2: Chart values selection sample - the column of values used for chart plotting.

After running the different simulation cases, approximately 92% of the 156 results figures showed a left (west)/right (east) mirroring of values. Although not exact, the lack of variation between the values of both sides is due to the incident angle which, in most of the clear sky cases, hits the panel and exits into the space in a similar way from both sides. However, similarity in this context does not denote any duplication; it means that the results from both sides are relatively close to each other. The difference between two similar nodes on different sides ranges from 5 to 500 lux. Such differences are significant for 9:00am simulation runs, when the sun rises from the east side, providing more illumination to the left-hand side of the space.

That being said, the third column from the left-hand side has been chosen to provide values for the analysis charts (Figures 6-2 and 6-3).

Figure 6-3 presents a sample chart for illumination level analysis. Each point on the chart corresponds to one node value in the DIVA results diagram, specifically in the third column from the left-hand side. The vertical axis represents the illuminance value in lux, while the horizontal axis represents the node distance from the window, which ranges from 0.50m to 7.50m. The blue dashed lines enclose the range of desirable illumination values, according to IES.

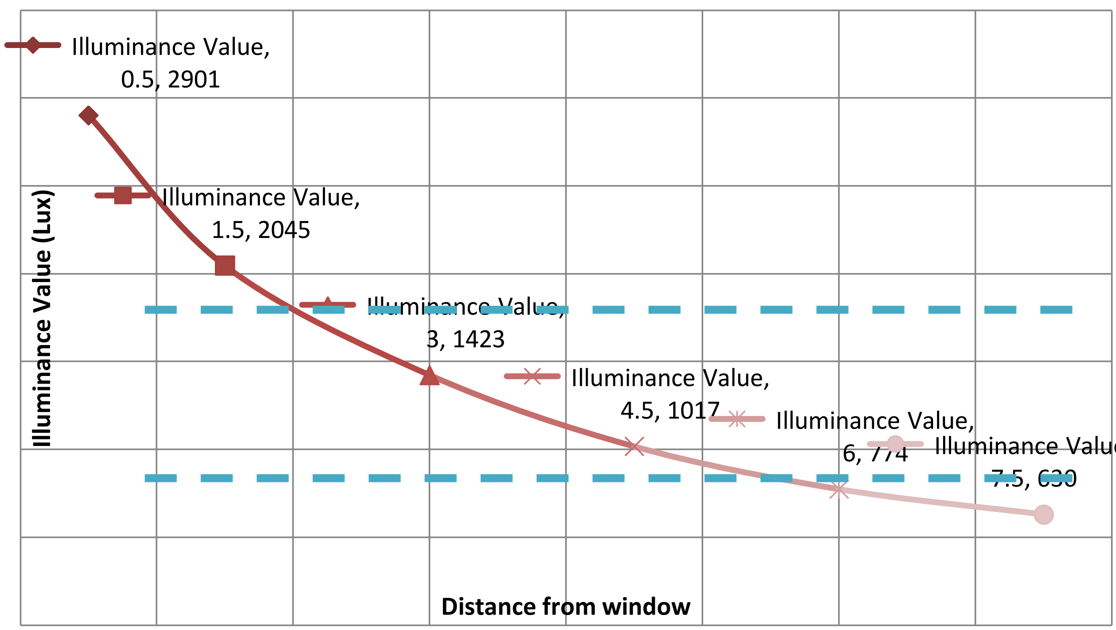

Figure 6-3: Chart sample - plotting illuminance values from previous figure.

6.1.2 KINETIC SCENARIO COMPILATION METHOD

The main objective of this thesis is to provide an extensible design algorithm for integrating daylighting performance into kinetic façade design. Thus, providing a manual compilation for a proposed kinetic scenario is useful and helpful for the reader to visualize the kinetic process in response to varying attributes.

Within the context of this study, louvers actuate in separate two-tilt-angle layers, to optimize the performance of daylighting inside the space. Over the course of a day, the secondary skin experiences different tilt-angle combinations to maintain adequate illuminance and light distribution inside the space. At the end of this chapter, the node-analysis diagrams are used to compile a kinetic scenario for different solar altitudes, based on those for June 21st and December 21st, at 9:00am and 12:00pm. This scenario provides an actuation pattern selected from the previously tested configurations for two different days.

6.2. SELECT CASE ANALYSIS UNDER CLEAR SKY

It is obvious that a south-facing space with glazing only will not maintain an optimal luminous environment, due to numerous reasons, among which are high illumination under clear sky conditions, and glare from direct illumination. Though this case shows high illuminance, regardless of the exact values, a base reference case is presented for comparative study purposes. But the useful reference cases here are those with lightshelf and external horizontal louvers, and not the case with full glazing.

In the first case analysis, two charts will be shown for each of the lightshelf and horizontal louver cases. One chart will show the overall illumination, accommodating the 36 nodes within the chart boundaries; the other is zoomed in and shows only the nodes falling under 5000 lux. The purpose of the zoomed chart and its narrower illuminance scale is to highlight the differences between node values. In the larger scale plot, these lines overlap.

As previously mentioned in Chapter 3, the performance criteria require that at least 75% of the surface area falls within the desired illuminance range. Thus, the contrast ratio is also based on the highest and lowest values within the 75% area. In this study, 75% represents 27 nodes.

6.2.1 LIGHTSHELF AND HORIZONTAL LOUVERS

A lightshelf does not necessarily yield more light at the back of the space, but blocks direct illumination at the front, which creates more even distribution.[94] The lightshelf used in the simulation was positioned at a vertical distance of 2.00m from floor level. It is 6.00m wide and 1.00m deep. The reflectance of the lightshelf was set to 90%. As shown in Figure 6-5, using the lightshelf as a daylighting optimization approach results in an undesirable interior luminous condition, where only 38% of the different times fall within the recommended range.

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[94] Schiler, *Simplified Design of Building Lighting*, 91.

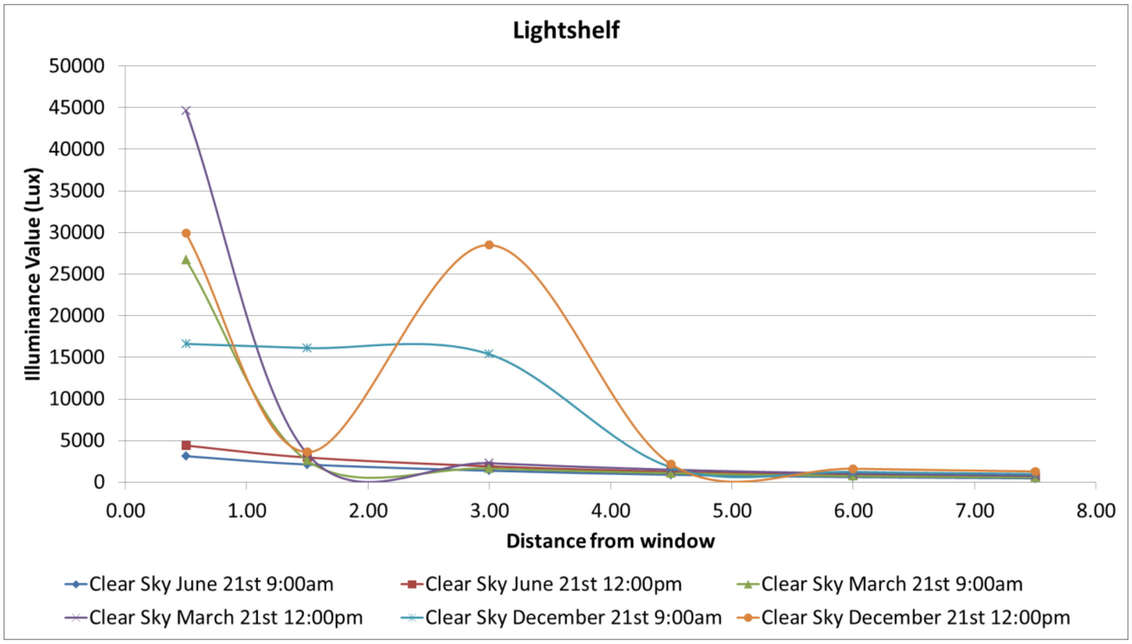

Figure 6-4: Lightshelf illuminance results - illuminance as a result of applying lightshelf.

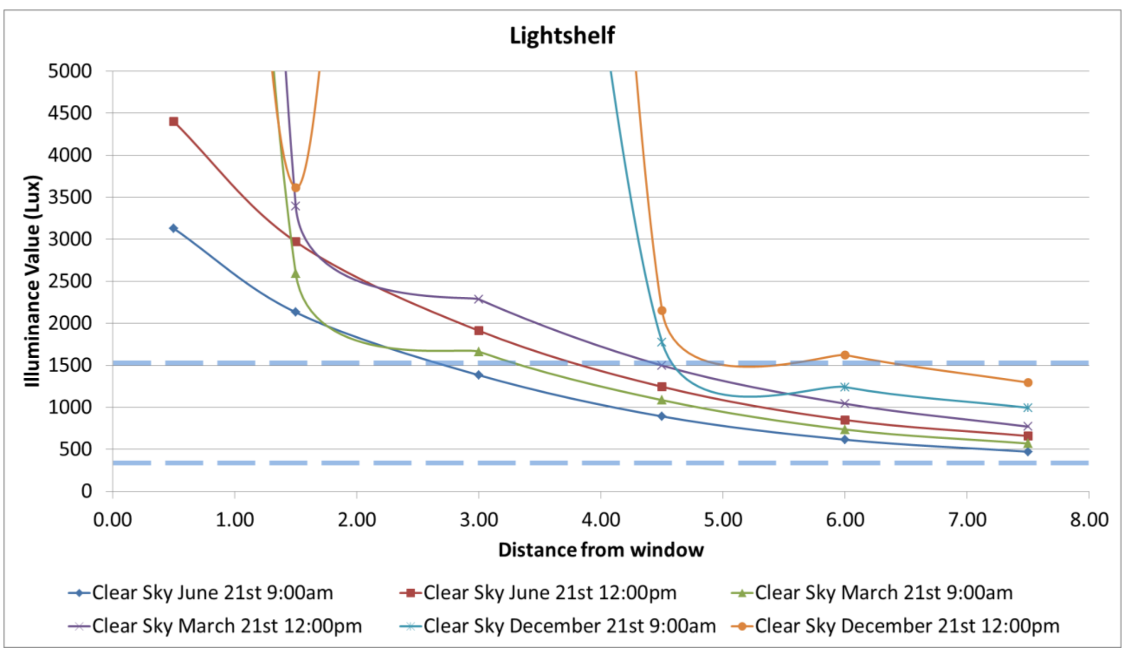

Figure 6-5: Zoomed lightshelf illuminance results - illuminance as a result of applying lightshelf.

At 3.00m from the window, the readings show a spike that reads 28,504 lux (Figure 6-4). The assumed explanation is that light of higher incident angle is reflected on the lightshelf upper surface, hits the ceiling at a short distance from the window, and then falls on the work plane. Also, the lightshelf condition results in a contrast ratio of approximately 35 between the highest and lowest illuminance values, which is not acceptable according to IES, or even the larger ratio of NRC; it goes beyond both recommendations.

Horizontal louvers are expected to block direct illumination at the front of the space, and also to redirect light deeper into the space. Replacing the lightshelf with a series of horizontal louvers impacts the quality and quantity of daylighting in the room. A noticeable change in the behavior of light is a more even distribution, and fewer high-value nodes (Figure 6-6). This change in external skin configuration results in better illumination than the lightshelf case; about 58% of the different times fall within the recommended range (Figure 6-7). Illumination nodes close to the window have smaller readings than those in the lightshelf case, which means that the horizontal louvers are more effective in blocking direct incident illumination at the front of the space.

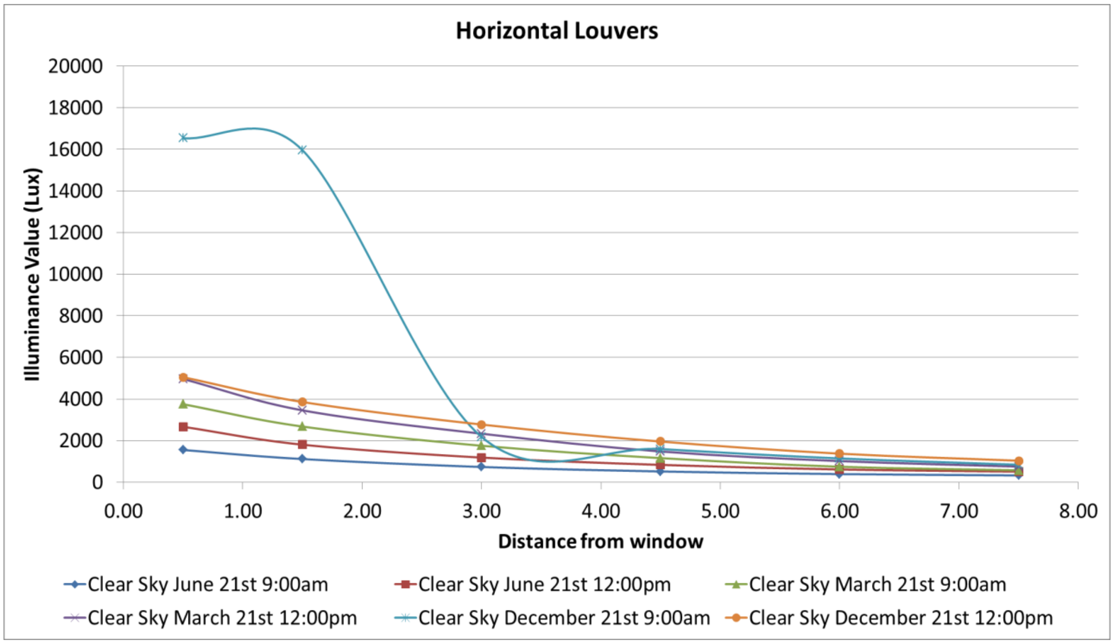

Figure 6-6: Zoomed horizontal louvers illuminance results - illuminance as a result of applying horizontal louvers.

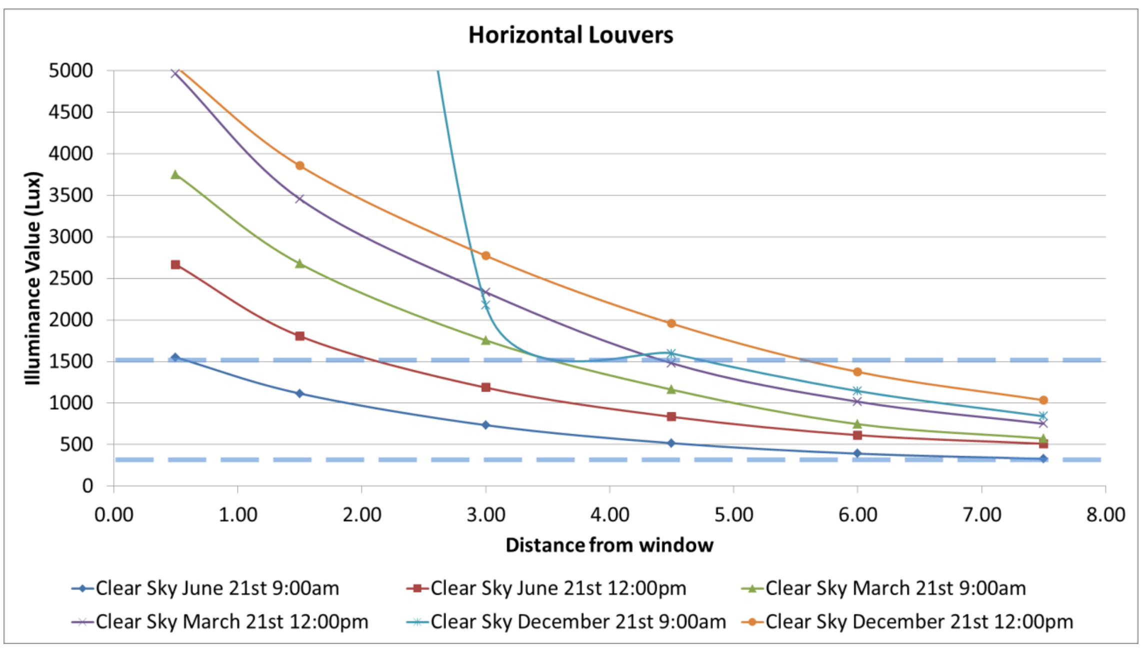

Figure 6-7: Horizontal louvers illuminance results - illuminance as a result of applying horizontal louvers.

With this skin configuration, the sectional nodes chart shows an even distribution in illumination levels along the cut line (Figure 6-6). Though horizontal louvers are effective in cutting down daylight in the room, they are not effective in bringing the illumination values into the desired range. As seen in Figure 6-7, the front of the space experiences high illumination at 9:00am on December 21st, due to a low solar altitude: 18º at this day and time. Compared to the lightshelf case, a spike at the front of the space is more acceptable than one in the middle, so it does not disturb the function of the space (Figures 6-4 and 6-6); however, this also depends on the furniture distribution inside the space. If the furniture is close to the window, it will not be considered an acceptable result, and vice versa.

6.2.2 SHADING CONFIGURATION 35º AND 55º

This case shows the performance of the secondary skin in shading configuration. The louvers do not have the same tilt angle. Rather, they are divided into two layers, with two different tilt angles on alternate louvers, 35º and 55º. This skin configuration was able to bring 61% of the times into a desirable illumination range. Moreover, this configuration showed successful results at 9:00am on December 21st and at 9:00am on June 21st; 71.4% and 77.2%, respectively, of the entire surface fell within the recommended illumination range (Appendix A). Though these values are not exactly 75% or higher, they are still close to the desired percentage.

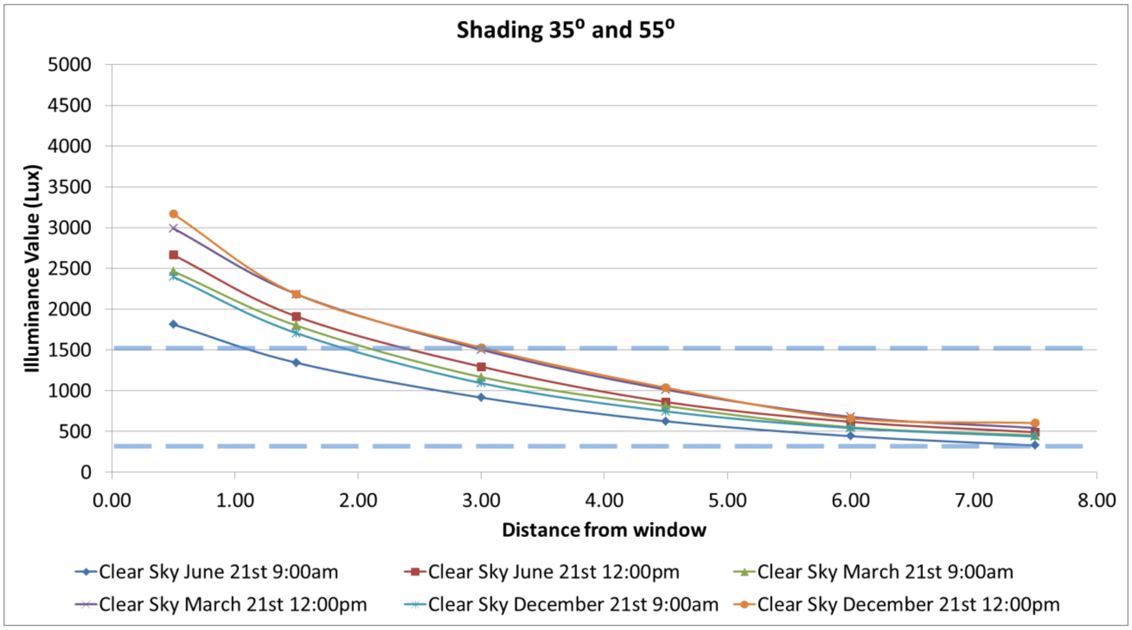

Figure 6-8: Shading configuration illuminance results - illuminance as a result of applying shading configuration of 35° and 55°.

This skin configuration resulted in a contrast ratio of approximately 10%, which according to IES is acceptable for decent space performance (Figure 6-8). A contrast ratio below 10 is preferred to maintain even distribution and eliminate false darkness perception, where the occupant incorrectly perceives certain spots as dark due to his exposure to extremely high illumination in other spots. There is no zoomed-in chart for this configuration, since all node values already fall below 5000 lux.

6.2.3 COMBINED CONFIGURATION 24° AND 156°

Within the framework of this study, angles below 90° indicate a shading configuration, while angles greater than 90° denote a harvesting configuration. In this case, the skin configuration is 50% in harvesting configuration, at 156°, and 50% in shading configuration, at 24°.

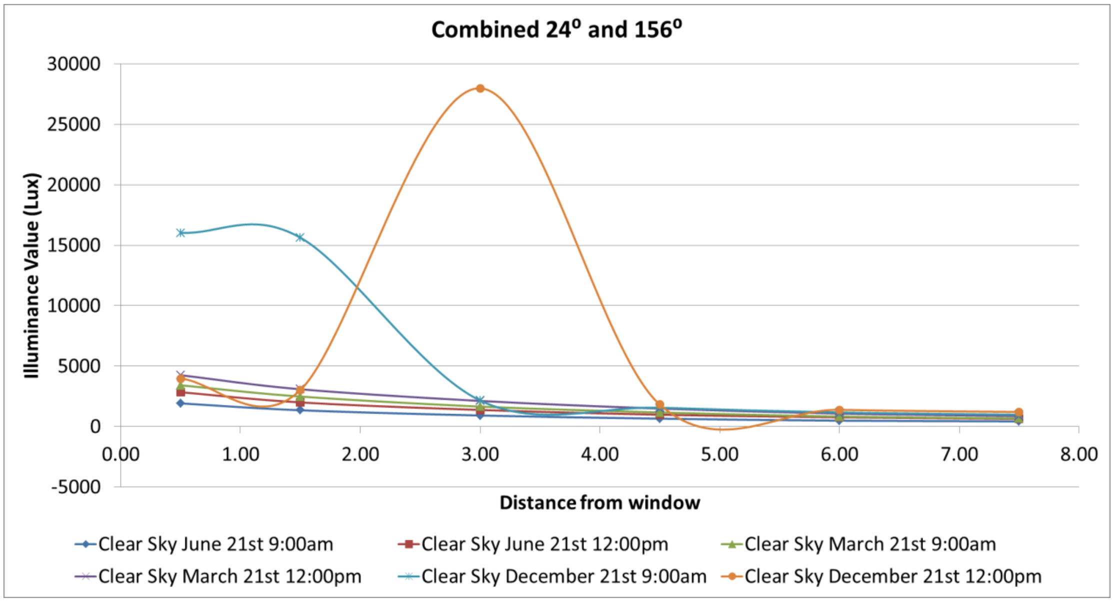

Figure 6-9: Combined configuration illuminance results - illuminance as a result of applying combined configuration of 24° and 156°.

This simulation run showed approximately 42% of the results falling within the recommended illumination range (Figure 6-9). If we compare this configuration against the horizontal louvers, we see that the horizontal louvers have better performance, with approximately 16% more nodes within range. However, this configuration brings more light into the middle of the space (Figure 6-10).

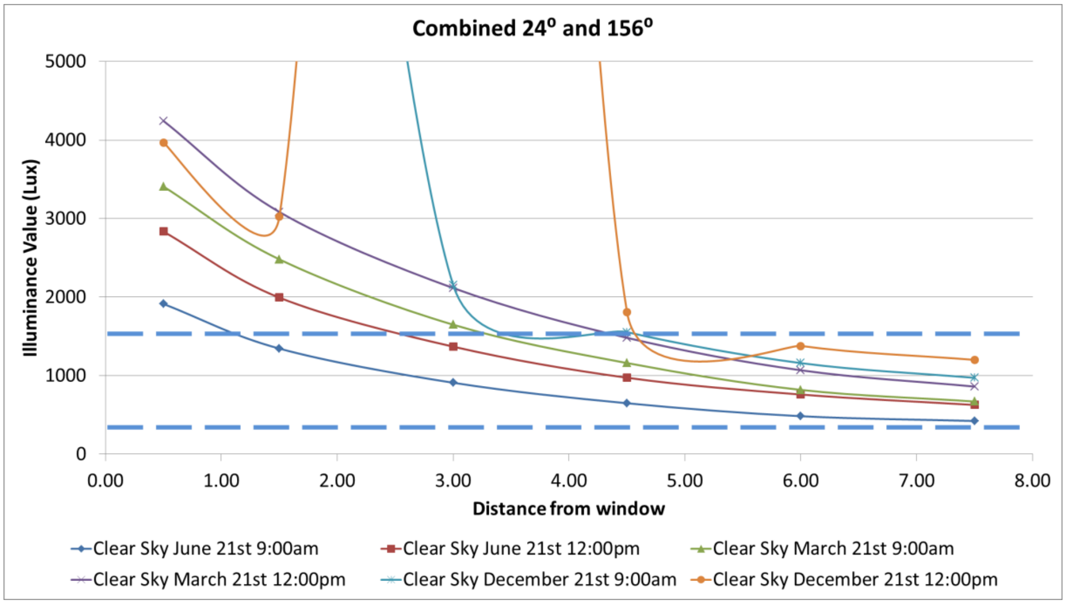

Figure 6-10: Zoomed combined configuration illuminance results - illuminance as a result of applying combined configuration of 24º and 156º.

A behavior that merits highlighting happens on December 21st at 12:00pm and December 21st at 9:00am. Beyond 4.50m, a steady daylight illumination takes place, running close to the upper boundaries of the recommended range. This interesting behavior presents the potential success of this configuration during those times, if a steady and even distribution is desired by the occupants at the back of the space, regardless of the hotspots at middle of the space. For full node-analysis values and diagrams, refer to Appendix A.

The most interesting part of this run is the contradictory behavior of daylighting inside the space on both times discussed previously, when the behavior of the light in the front half of the space is significantly different than that at the back of the space. The observed conclusion about this scheme is the good performance of the skin beyond 4.50m, reaching the last node at the back of the space. Also, Figure 6-10 shows great potential for this configuration to bring light within the desired range to space even beyond 7.50m. This behavior fits the demand for intelligence in kinetic façades. For example, this configuration may be used if the space sensors detect that only the back of the space is occupied, or that occupants working at the back are executing less critical tasks that do not require high illumination. However, the contrast ration is higher than desired by IES; it is 13.50, which is acceptable according to National Research Council of Canada (NRC).

6.2.4 COMBINED CONFIGURATION 26^o AND 163^o

On June 21st, at 9:00am, this skin configuration was able to achieve illumination of 82.9% of the entire room surface area within the recommended range (Appendix A); only the front 1.50m falls out of range. This makes the entire space, except the front strip, optimal for occupancy with acceptable luminous conditions. The skin shows a successful attempt to provide daylighting deep into the space within the acceptable range (Figure 6-11).

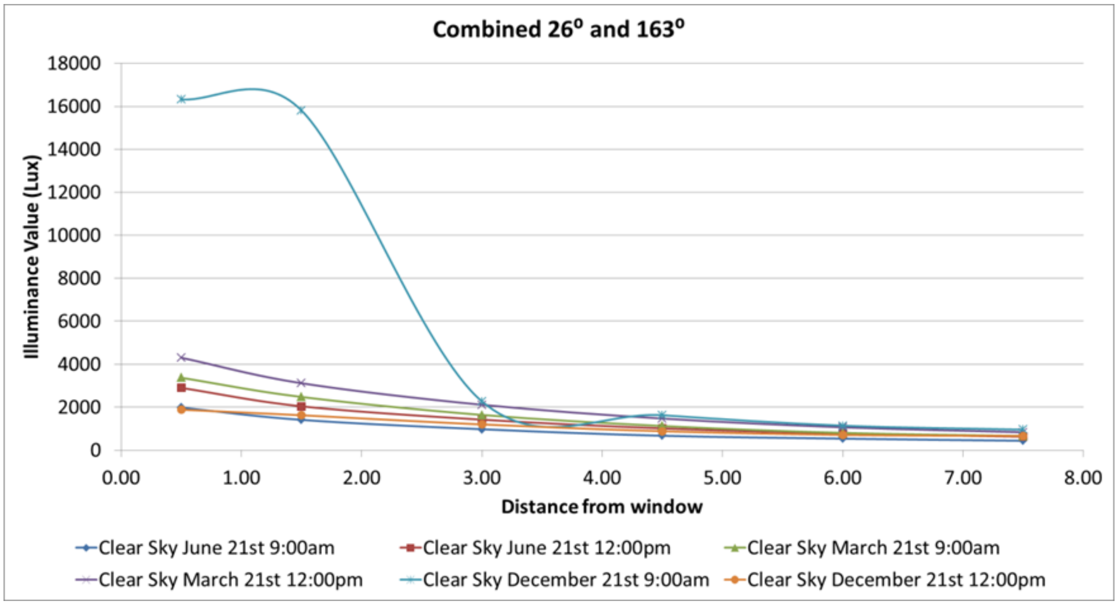

Figure 6-11: Combined configuration illuminance results - illuminance as a result of applying combined configuration of 26° and 163°.

If we are to evaluate the luminous distribution (contrast ratio), we will consider all times except the December 21st 9:00am result, when the readings showed high values at the front of the space, unlike the majority of the other runs. The contrast ratio of the highest to lowest values in the space is 6.25 which is acceptable according to the IES recommendation (Figure 6-11).

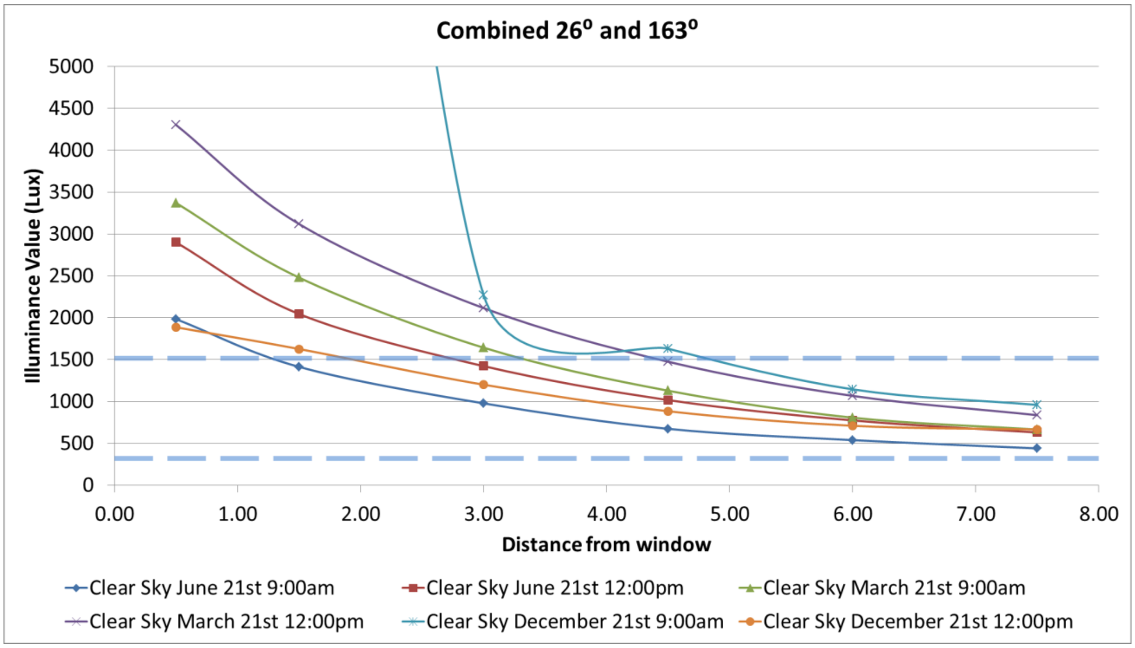

Figure 6-12: Zoomed combined configuration illuminance results - illuminance as a result of applying combined configuration of 26º and 163º.

6.3. OVERCAST SKY CONDITION DISCUSSION

An overcast sky condition is three times brighter at the zenith than the horizon, since water particles refract and reflect all wavelengths of sunlight.[95] The calculation of daylight factors is usually done with an overcast sky condition, since daylight factors do not account for direct illumination. For this study, illuminance simulations were run under overcast sky conditions to see if the algorithm provides the potential to find an optimal solution for specific skin configurations.

Given that direct illumination does not accompany overcast sky conditions, the performance of horizontal louvers is expected to be limited. However, since overcast skies are possible in the

[95] Ander, *Daylighting performance and design*, 85.

real world, three different skin configurations were tested for daylighting performance. The interesting observed behavior in daylighting at all times for the three configurations is that more than 75% of the nodes fell within the desired illuminance range for the cases shown in Figures 6-13 and 6-14. Changing the configuration from one to another impacted the indoor luminous environment in terms of illuminance values and distribution.

The harvesting configuration shows approximately 78% of the times within range, with a contrast ratio of approximately 5. However, this configuration does not enhance illumination at the back of the space, where below-range levels are experienced at certain times. It is more successful in the middle of the space (Figure 6-13). It is obvious that the illumination range under an overcast sky is smaller than under a clear sky.

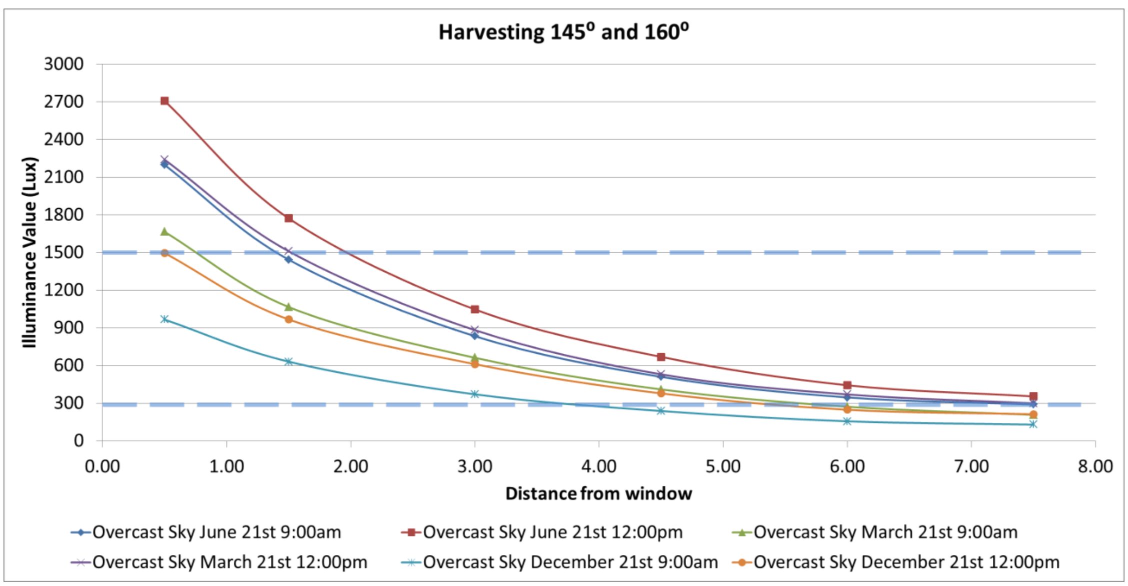

Figure 6-13: Harvesting configuration illuminance results - illuminance as a result of applying harvesting configuration of 145° and 160°.

The skin configuration was changed to 10° and 70° for another simulation test run. Compared to the harvesting configuration, this configuration maintained almost the same illumination level at the back of the space, while decreasing illumination at the front of the space, bringing it into a more desirable level (Figure 6-14). Approximately 81% of the times fall within the desired range, and the contrast ratio is maintained at 5; though if we include 100% of the nodes, the contrast ratio is 12% - which is still close to 10%. This scheme shows successful illumination from the front to the middle of the space. On June 21st at 12:00pm, 77.2% of the entire space nodes fall within range, which makes this configuration a potential solution for the kinetic skin actuation at this time.

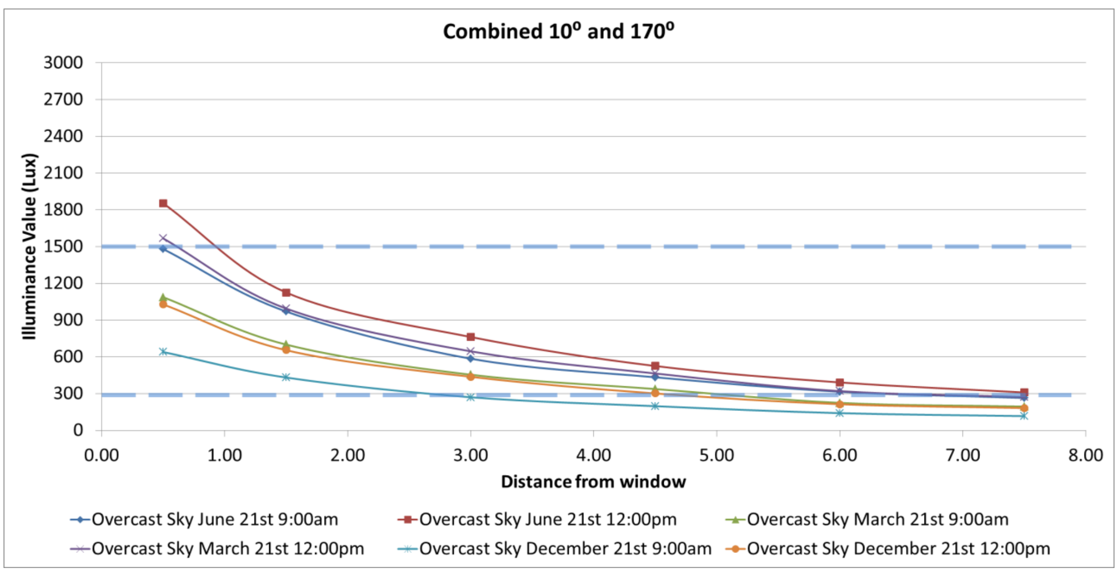

Figure 6-14: Combined configuration illuminance results - illuminance as a result of applying combined configuration of 10° and 170°.

Switching from a combined configuration, where every other louver has the same tilt angle, to the combined-split scheme, where the upper half of the skin has the same tilt angle, and the bottom half has a different angle, resulted in minor changes in the illumination levels. These changes are within the desired range (Figure 6-15). While the combined-split scheme is expected to block light at the bottom of the space, and to bounce light into the back of the space through the upper portion of the skin, the results do not show major variation from the previous combined scheme. While the results do not show major variation, 26 nodes fall within the recommended range, giving an acceptable percentage of 72.2%. This may have been a consequence of the spacing between the louvers, the size of the louvers, or the offset distance of the secondary skin from the glazing; thus, these factors should be studied at a future stage. This configuration might have proven efficient when applied on smaller elements like venetian blinds.

If analysis is to be provided for the overcast sky condition, it should focus on the ineffectiveness of light-deflection elements to influence the behavior of the luminous environment inside indoor spaces. The absence of direct illumination in an overcast sky condition is the main reason for the ineffectiveness of the system; less light is bounced off the surfaces of the louvers, resulting in less illumination values inside the space. This is a very common interpretation in the field of daylighting for overcast sky conditions.[96] In Appendices A and B, more node-analysis diagrams and sectional illuminance results are shown.

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[96] Schiler, *Simplified Design of Building Lighting*.

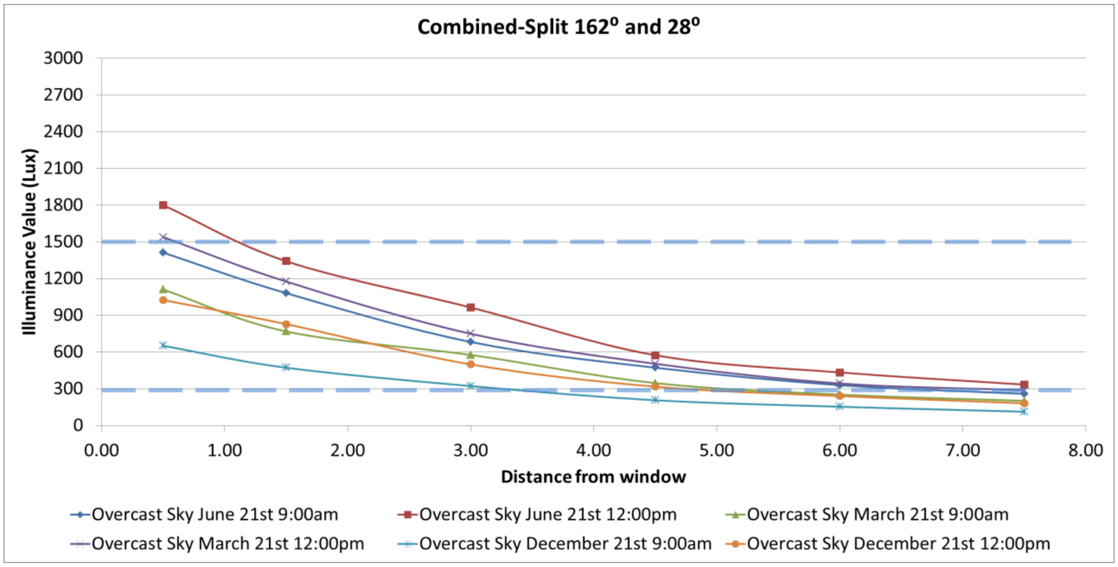

Figure 6-15: Combined-split configuration illuminance results - illuminance as a result of applying combined-split configuration of 162° and 28°.

6.4. KINETIC SCENARIO FOR ACTUATION PATTERN

Given the main objective of this thesis, showing a proposed actuation pattern for the secondary skin is important. The proposed configurations are not limited to the analyzed ones, but include all simulated schemes (Appendix A). Though the compilation of this scenario may not be successful at this point, due to the limited number of simulation runs, it would be helpful to provide an idea about how the kinetic system is intended to operate. For a complete scenario, the algorithm-based definition should be used as was originally intended.

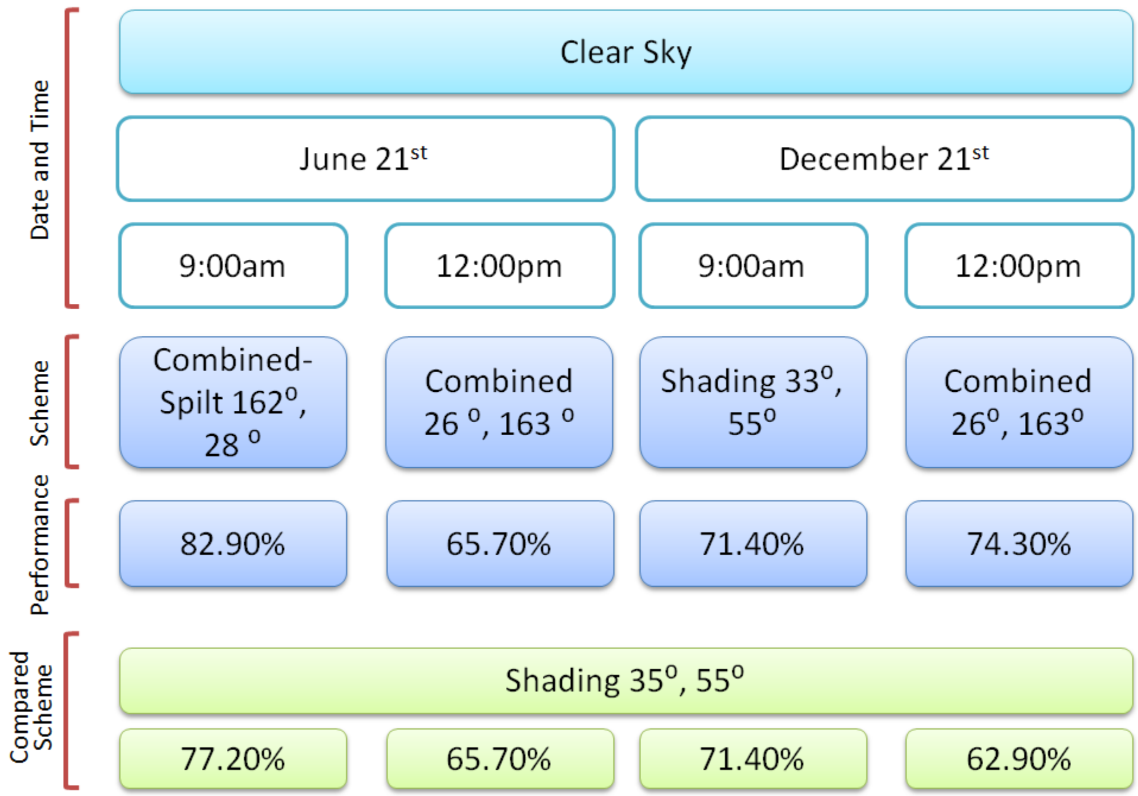

Figure 6-16: Compiled scenario for clear sky - the best configuration selected from simulated cases.

Figures 6-16 and 6-17 present a proposed scenario for the best skin performance available from the simulation cases run for this study. They do not necessarily represent the optimal solution, but the best available selection from the manual simulation cases. The algorithm should be able to automatically generate numerous configuration iterations and provide the designer with an optimal one.

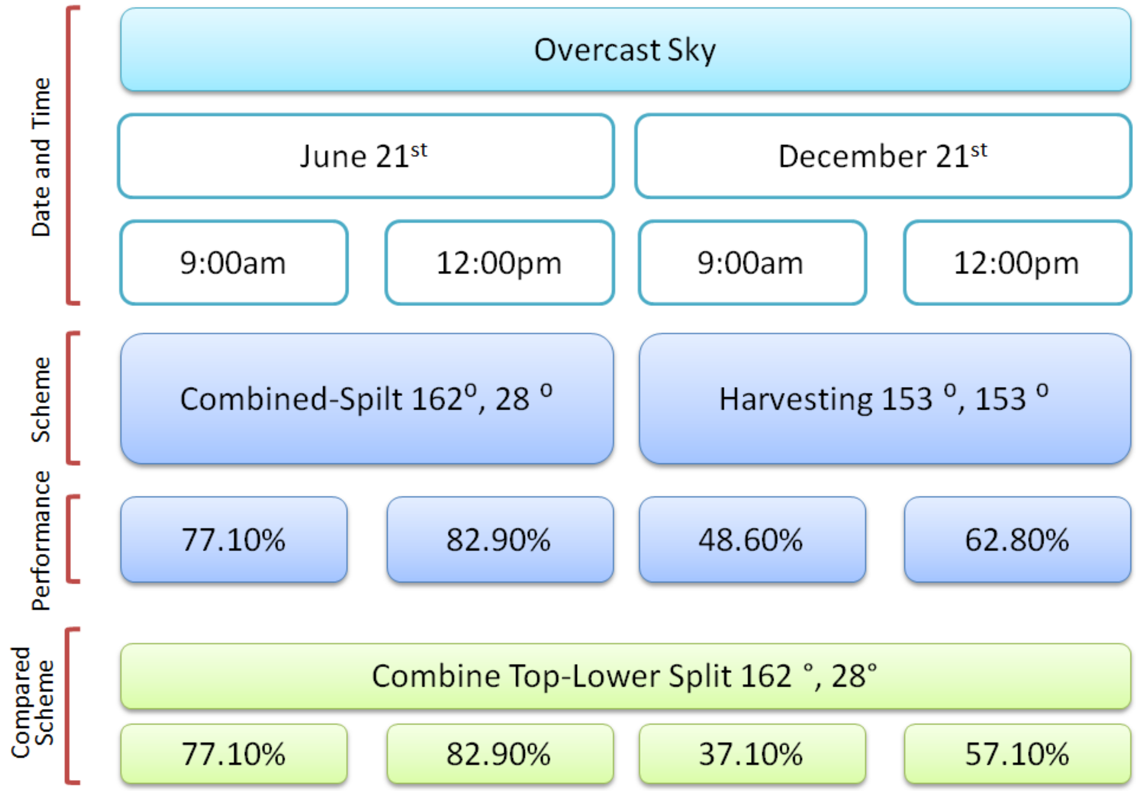

Figure 6-17: Compiled scenario for overcast sky - the best configuration selected from simulated cases.

Each scheme is accompanied by a "performance" value underneath. This value represents the percentage of illuminance nodes, on the entire surface area, that fall within the recommended range. While the proposed performance percentage in this study is 75%, some of the manually simulated cases did not achieve this percentage, but were close. However, there is potential for finding at least one optimal configuration for each specific date and time.

6.5. ANALYSIS CONCLUSION

In conclusion, a chart has been developed to show the percentage of nodes that fall within the recommended range for each configuration at different times of the year (Table 6-1). The configuration of the secondary skin with different tilt angle has infinite possibilities; thus, the use of parametric software is more efficient in determining possible configurations than doing so manually. Table 6-1 shows the selected configuration for the manual simulation runs. It does not mean that the kinetic skin will use these cases only for actuation; it is a limited study due to the endless possibilities and time limitations. Thus, if some of the cases didn't show successful results, it does not mean that the study fails. It is just about running more possibilities and finding the best among all of them.

Secondary Skin Configuration	Percentage of points within acceptable illumination range											
	Clear Sky						Overcast Sky					
	December 21st		June 21st		March 21st		December 21st		June 21st		March 21st	
	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm
Glazing Only	37.10	20.00	74.30	60.00	54.30	42.90	42.90	42.80	48.60	54.30	42.90	48.50
Lightshelf	37.10	22.90	68.60	54.30	57.10	48.60	34.30	48.60	54.30	60.00	57.10	51.50
Horizontal Louvers	40.00	31.40	85.70	71.40	51.40	45.70	14.30	37.10	51.40	62.90	31.40	51.40
Shading 0, 45	51.40	48.60	82.90	65.70	62.90	48.60	22.90	40.00	57.10	60.00	42.90	60.00
Shading 10, 45	57.10	48.60	82.90	65.70	65.70	54.30	13.30	31.40	48.60	57.20	37.10	48.60
Shading 35, 55	71.40	62.90	77.20	65.70	68.60	62.90	14.30	25.70	42.90	48.60	28.60	42.90
Harvesting 145, 160	25.70	2.90	82.90	65.70	34.30	20.00	42.90	62.80	65.80	65.70	54.30	62.90
Harvesting 153, 153	25.70	2.90	82.90	65.70	34.30	8.60	48.60	62.80	60.00	68.50	54.30	68.60
Combined 10, 170	34.30	20.00	82.90	65.70	51.40	37.10	31.40	51.40	71.40	77.20	51.40	68.60
Combined 24, 156	42.90	31.40	82.90	65.70	54.30	48.60	31.40	51.40	62.80	71.50	57.10	62.80
Combined 26, 163	42.90	74.30	82.90	65.70	57.10	48.60	31.40	48.60	65.70	77.20	54.30	74.30
Combined 55, 168	51.40	42.90	77.10	54.30	57.10	48.60	31.40	57.10	57.10	57.10	51.40	71.40
Top-Lower Split 162, 28	34.30	20.00	82.90	54.30	51.40	42.90	37.10	57.10	77.10	82.90	62.90	71.40

Table 6-1: Performance percentage table - the percentage of nodes falling within recommended illumination range.

The table shows the effectiveness of the configurations used for simulation during high solar altitude, especially on June 21st. The blue-highlighted values are greater than 70%, while the grey-highlighted values are greater than 60%. If we are to consider one configuration, as a static system, for the simulated space, the space will experience inefficiency in the luminous environment over the course of the year, because one configuration cannot enhance daylighting at all times. It may be efficient during certain periods and altitudes, but not during others. For example, the combined 26-163 configuration works best on December 21st at 12:00pm and June 21st at 9:00am, under a clear sky, and June 21st at 12:00pm and March 21st at 12:00pm, under overcast sky conditions. We can make use of this configuration during these times and find better configurations for the other times.

Moreover, a static system may not be efficient for changing externally and internally reflected components. A kinetic system is expected to actuate in response to any of these changes, to enhance the luminous environment. Whether kinetic or static, the system will not show effectiveness in low solar altitudes, where horizontal louvers are not effective in blocking low sunlight. Thus, the geometry of the skin should be considered as part of the future work; there may be a possible skin transformation that is capable of blocking high-angle and low-angle sunlight.

7. CHAPTER 7 CONCLUSION AND FUTURE WORK

This chapter provides a summary of the work presented in this thesis and the concluding discussion based on the proposed algorithm and simulation runs, as well as presenting possible future work for the development of this thesis topic.

7.1. CONCLUSION

Daylight deflection is about redirecting light into a space or back to the outdoor environment. In real life, shading elements are closed during high solar gain, which results in dark interior spaces and the use of artificial lighting. This waste of energy can be overcome by incorporating a combined scheme of shading and harvesting in one skin configuration. Using both strategies in a combined scheme is possible, and may result in more efficient and better daylighting performance inside office spaces. The hypothesis presented in this thesis, stating that “one way to achieve appropriate daylight harvesting is through the use of advanced daylight deflection strategies involving an intelligent kinetic façade,” has been proven in its initial stage, which showed the potential of the tool’s success by running manual simulation of select tilt angles.

A study of the simulation of secondary skin configurations and their impact on daylighting performance inside office spaces was conducted. The study was split into two sections: an algorithm-based design tool for designers and a manual simulation that provided the reader with a brief introduction of how the tool is intended to work. This thesis hypothesizes that the use of light-deflection techniques in intelligent kinetic façades may enhance the luminous indoor environment and adapt to changing environmental conditions and occupants’ needs, though not all factors were simulated in the context of the work. Since only a limited number of different skin configurations were simulated, the hypothesis was not completely proven correct, but initial results show that it is likely to be correct. The success of the system is dependent on running hundreds of configurations using a genetic algorithm tool - in this study, Galapagos.

However, the success of certain configurations, at certain times of the year, reflects the potential for the success of this hypothesis, considering that the façade is intended to actuate and change configuration according to different times of the year.

The external skin actuates to optimize daylight-deflection, maintaining a desirable luminous indoor environment at certain times of the year, as previously shown in Chapter 6 for some cases. The louvers rotate using the concept of independent tilt-angle, where every other louver has the same tilt angle. The louvers could be configured for harvesting, shading, or use a combined configuration. When skin configuration changes, due to louver actuation, the algorithm is designed so that DIVA detects the alteration and instantly reflects it onto a calculation grid inside the space. This allows the designer to run numerous iterations, during the design stage, and select the best possible one based on pre-defined criteria.

A genetic algorithm was incorporated into the definition to enable a search of the best skin configurations at specific dates and times or under different sky conditions. Genetic algorithms work to find an optimal solution – but not necessarily the best solution – under certain parameters and conditions. These parameters could range from users' desired illumination levels, to externally-reflected daylighting components. In this study, one actuation parameter and three performance indicators for daylighting were defined. Occupants' behaviors were indirectly incorporated into the algorithm through the ability to change the range of acceptable illumination, which denotes changing occupant tasks that could be automatically detected by intelligent space sensors and cause re-adjustment of the desired range based on the task being performed.

The proposed algorithm is extensible. It is open to additional parameters and performance indicators, which makes it more complex for better performance assessment. Changes in any of these parameters trigger the system to run and find an optimal configuration for the skin, in order to maintain the desired luminous environment. Due to technical difficulties experienced with the DIVA component in importing node values into Grasshopper, manual simulation was implemented for select configurations, based on previous research work[97] in similar areas.

DIVA was used as the simulation tool for the manual study, using "Radiance" as its calculation engine. DIVA, using Daysim, which runs in the background for calculation, has already been verified against another tool, 3ds Max Design, for accuracy and reliability, and it was found that both tools produce similar results for sidelit spaces[98]. Running this tool for manual simulation of the modeled space gave various results for different times of the year. None of the simulated skin configurations showed acceptable results on all simulated dates. Each configuration showed effectiveness, based on the thesis's criteria, at certain times and dates, some of which were under clear sky conditions and some of which were under overcast sky conditions. Since the purpose of the study was to find at least one time for each configuration when it is successful in bringing daylighting levels into a desirable range, so that this configuration could be used in a kinetic scenario for that time, this behavior would be acceptable.

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[97] McGuire, "A system for optimizing interior daylight distribution..."

[98] Reinhart and Breton, "Experimental Validation of Autodesk (R) 3ds Max (R) Design 2009 and Daysim 3.0."

Among the simulated configurations, only one scheme showed the potential to handle very low solar altitudes under clear sky conditions. Scheme "shading 35°, 55°" gave the result of 71.4% of nodes falling within the desired range on December 21st, at 9:00am, with a solar altitude of 18°. This means that different skin geometries should be tested for better handling of lower angles, or more skin iterations should be generated and tested. Most of the other configurations were successful under the same sky condition, on June 21st, at 9:00am, with a solar altitude of 50°, when most of them were above 75%.

The analysis was extended to evaluate the luminous distribution of illumination levels inside the space. This provided a daylighting contrast ratio. Most of the runs at different times showed a contrast ratio less than 10%, taking into consideration that the compared values were within the lowest 75% of the entire space. Generally, many cases showed 5% as a common approximate value for contrast ratio, with some exceptions going beyond the desired 10%. The average contrast ratio for the simulated cases was 8.3%, based on the 75% surface area. Future work could include a more meaningful overview and research about glare and how to activate a façade to provide useful illuminance levels while avoiding both high contrast of light in the interior space and direct glare.

Overcast sky conditions without a direct illumination component were also considered in the simulation. The secondary skin systems provided almost the same number of times when the louvers were able to successfully bring illumination into the appropriate range. While most cases showed only a couple of successful times, the space showed smooth blending of illumination levels across the entire area, and the highest values shown were close to the highest desired. Some cases did not show successful illuminance values, but did show a successful desired contrast ratio. Under this sky condition, altering the skin configuration was found to be slightly effective, which highlights the absence of the direct illumination component. Thus, the successful different times of the year had almost the same distribution, as illustrated in Chapter 6.

This study shows that kinetic façades have a greater potential to enhance the indoor luminous environment than static façades. In Figure 7-1, a comparison between a kinetic scenario and fixed façade tilt angle is presented. While the actuation of the louvers impacts the performance of daylighting inside the space, and brings it into the desired performance range, applying a fixed tilt angle to the louvers results in poor daylighting performance compared to the kinetic case. This example shows the effectiveness of the “combined 55, 168” scheme on June 21st, at 9:00am, and its inefficiency at the other three times. This is the disadvantage of static systems: they cannot adapt to changing solar conditions.

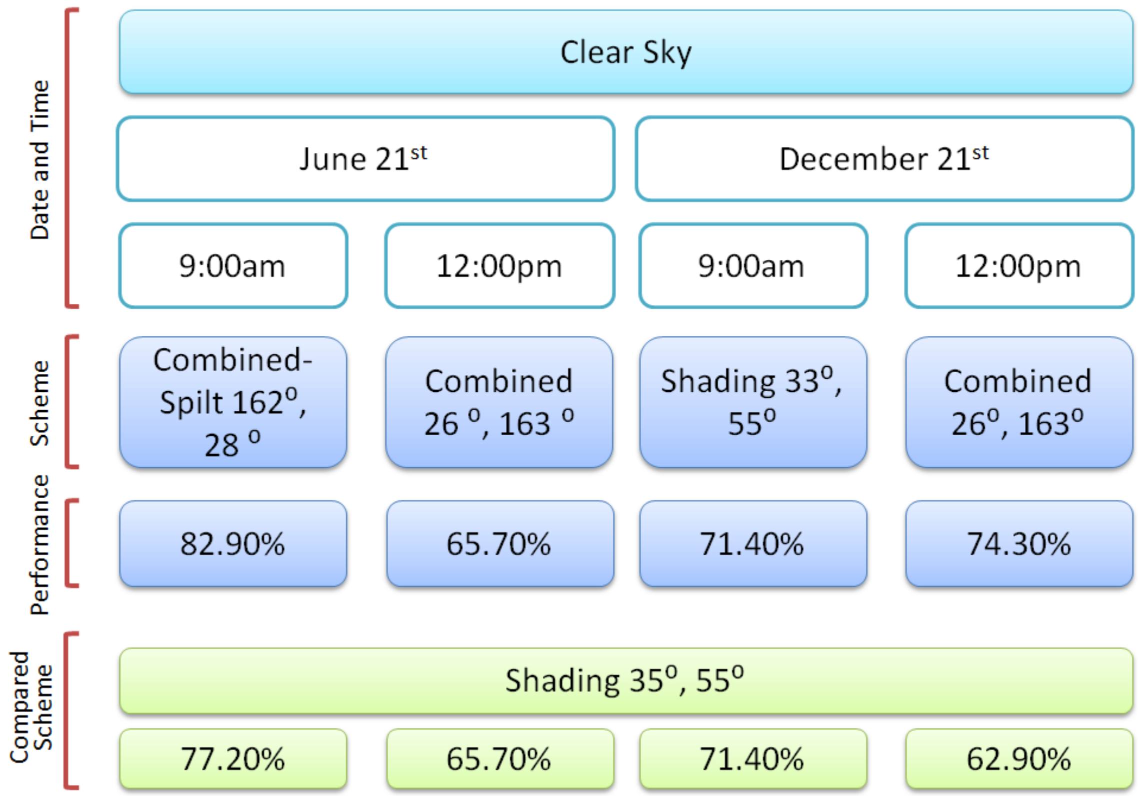

Figure 7-1: Static versus kinetic - results of the performance of a kinetic façade versus a static façade over four different times of the year.

7.1.1 SCOPE AND LIMITATIONS

The science of daylighting assessment includes many different attributes and not just those discussed in the previous chapters: illumination levels, luminous distribution (contrast ratio), and the penetration depth of daylighting into the back of the space. Due to time limitations, only these three attributes were studied, thus narrowing down the scope of this thesis to evaluating the illuminance value inside the space, and comparing the nodes to each other to discuss the luminous distribution and penetration depth.

Four major limitations are discussed below: technical difficulties with the software, the lack of modeling of the external building surfaces, the absence of realistic occupant behavior modeling, and the absence of furniture inside the space.

A number of limitations were experienced over the course of this thesis, among which was the data exchange between DIVA-in-Rhino and the Grasshopper component. DIVA 1.1 was unable to extract the illuminance node values and bring them back into Grasshopper. This limited its effectiveness for the performance criteria evaluation as the simulation could not then use the genetic algorithm component to find an optimal solution for a specific date and time. Theoretically, the algorithm should be run properly to find solutions for specific design problems. The results had to be manually extracted to test the algorithm, as shown in Chapter 4. Rather than running the algorithm through the genetic algorithm component, a manual simulation had to be run for select configurations, based on previous work in similar areas of study[99]. The manual simulation involved running 13 different configurations for 6 different times of the year under clear and overcast sky conditions. This technique had its drawbacks, and the selected configurations are not necessarily what the algorithm would have picked as optimal solutions. There could be better solutions that have not been simulated within the framework of this study. Thus, running more skin iterations would be a useful step if done as future work. A better solution, however, is to wait until the next release of DIVA when that limitation might be fixed.

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[99] McGuire, "A system for optimizing interior daylight distribution..."

A major element of the urban surrounding context is the external building surfaces. These surfaces have certain reflectances and light reflection properties. Given that the simulation has been run on a generic office space, the calculation does not account for surrounding context, which could have impacted the indoor luminous environment depending on the location of the office. This limitation could have changed the behavior of daylighting inside the space by adding another layer of calculation, the externally reflected daylight component.

Moreover, this thesis addresses the integration of intelligent features into the building façade. Such features are intended to be used for occupant behavior detection and to make the façade react with consideration for this behavior. The proposed tool does not integrate directly an occupant model, due to the limitation of scripting in this area; however, the tool integrates an indirect approach for taking into account one attribute of human behavior. The possibility of changing the desired illuminance range according to the tasks performed inside the space symbolizes the detection by sensors of changing occupant activities and tasks, requiring different acceptable illumination ranges.

Different actuation schemes impact the performance of daylighting inside the space. Some configurations maintain better illumination at the back of the space than the front area and vice versa. Accordingly, deciding on the best solutions should take into account the furniture layout, which has not been taken into consideration in this study. Depending on the location of the workplanes inside the space, the secondary skin will actuate to optimize the quality and quantity of daylighting in these areas. For example, if the architect decides that furniture will be located closer to the window, the louvers will actuate to bring the front portion of the space into the desirable range of illumination and luminous distribution.

7.2. FUTURE WORK

The proposed algorithm is designed to assess the performance of the secondary skin in optimizing illumination, luminous distribution, and depth of penetration, but it does not take into account many other factors, among which are glare, heat gain, different space function, skin geometry, and surrounding urban context. Figure 7-3 shows the suggested additions for future development of the algorithm. These include occupant behavior, glare remediation, heat gain and thermal comfort, skin geometry, and surrounding urban context.

7.2.1 OCCUPANTS' BEHAVIOR

The behavior of occupants is an independent topic on its own; however, some layers of the topic could be incorporated into the proposed design algorithm. While the algorithm incorporates a simplified symbolization of occupant behavior, as previously mentioned in section 2.2, it does not integrate more complex layers of human behavior, such as detecting changing tasks and working moods through facial recognition techniques. Integrating this attribute into the algorithm represents an important step in the development of this area of study; it could be one step to better performing architectural spaces. In a user empowered version, he might be able to change the performance specifications of the system to suit his work location, work time, and preferred illuminance levels to enable a different set of louver activation.

Carniege Mellon Robotics Institute has an established research center called "People Image Analysis Consortium" that researches human behavior and facial recognition[100]. The image below shows the architecture of detecting human behavior and facial emotions. The institute's website provides an example and coding for different techniques of behavior detection. A possible way of integrating this into the proposed algorithm is using one of the designed codes provided by Carniege Mellon as a reference for developing a similar technique using Grasshopper scripting, maybe with the aid of a third interface for human agent and behavior detection.

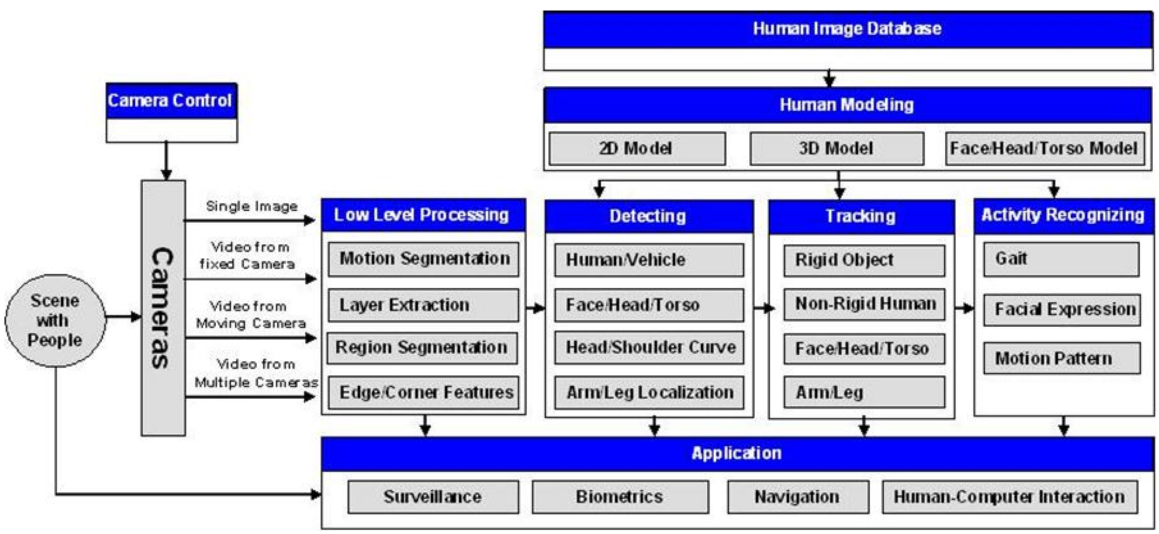


Figure 7-2: Architecture for human behavior detection system - the architecture of detecting human behavior and facial emotions.[101]

[100] "PIA Carnegie Mellon Robotics Institute."

[101] Ibid.

7.2.2 GLARE REMEDIATION

Glare is a crucial problem in architectural spaces such as offices, hospitals and museums. Simply, it is caused by direct light falling on the workplane – whether vertical, like computers, or horizontal, like desks – or hitting the occupant's eyes. Accounting for glare in office spaces, in addition to the three performance indicators explored in this study, would make this design tool much more useful. Calculation and assessment of glare conditions inside the space may be incorporated through using DIVA and glare calculation equations. Defining performance criteria for glare that can be expressed in the form of parametric calculation components is necessary for the execution of this development. Although this is more complex than calculating illuminance levels, it is possible to predict potential glare locations, suggest mediation before the building is constructed, or provide an activation pattern for the louvers that results in a few number of glare incidents.

7.2.3 HEAT GAIN AND THERMAL COMFORT

Allowing sunlight to penetrate into architectural spaces is sometimes good for illumination and energy-saving, if appropriately controlled according to desired preferences. However, direct sunlight always carries heat that affects the thermal comfort inside the space. This study does not take into consideration heat gain and thermal comfort. It would be more valuable to optimize daylighting and thermal comfort inside the space using the same algorithm-based design tool.

7.2.4 SKIN GEOMETRY

Within the framework of this study, the actuation of the louvers in rotational motion is tested for daylighting performance. But this is not the only parameter that can enhance the quality of the indoor luminous environment. Changing the geometry of the secondary skin, the louvers' shape, and the actuation pattern, may have impact on the performance of daylight harvesting. This parameter, specifically, adds not only to the performance of the space, but also to the aesthetic aspect of architecture, which makes it an exciting potential attribute for future exploration. Varying geometry parameters would allow architects to produce numerous iterations for skin design and find an optimal design that matches the aesthetic requirements and the desired performance of the luminous environment.

7.2.5 SURROUNDING URBAN CONTEXT

Adding a layer of surrounding urban context to the simulation model is important, especially in architecturally-dense cities, like Los Angeles, where every project is affected by neighboring building on an urban and architectural scale.

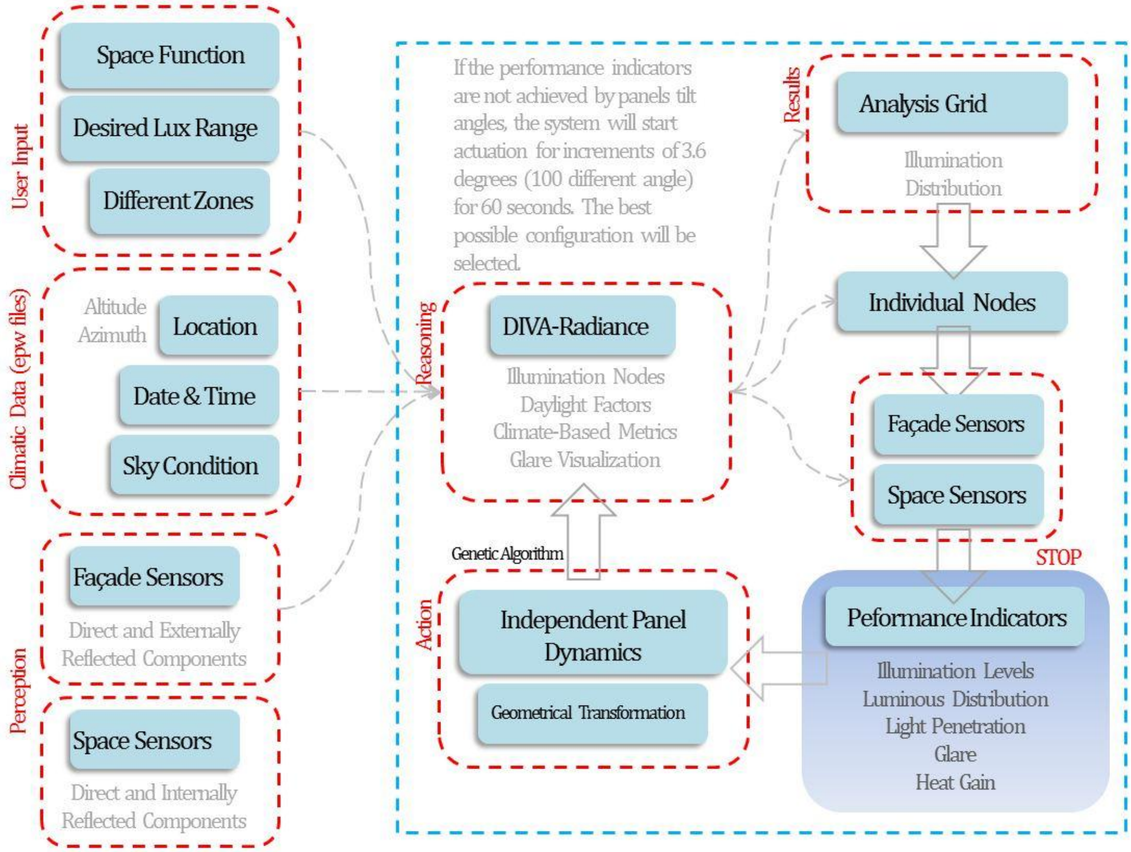


Figure 7-3: Algorithm logic for future work - additions to the extensible algorithmic design tool as future development for the investigated topic.

7.3. SUMMARY

In conclusion, a high integration of design and research flowing between architects, computational designers, and consultants is important to achieve innovation and efficiency. Communicating to the designer the importance of integrating performance-based approaches at the early design stage, and their impact on the design, may shift the logic of executing an architectural project. The integration of daylighting factors into the design phase, through design tools and computation, results in the improved performance of daylight harvesting and therefore tackles issues of human comfort and energy efficiency. Taking into consideration human behavior in the simulation will enhance the performance of an architectural space in terms of energy-consumption.

Assessing the performance of intelligent systems in buildings does not have an absolute benchmark; it is a relative evaluation process that depends on the occupants' needs and preferences, and the function of the space. Accordingly, the presence of occupants-model during simulation is necessary for efficiently investigating the topic. Simulating such models in the study expands the layers of investigation and results in more complex algorithm; however, it is important to the development of the performance-based design area in architecture.

People involved in the design and construction process can have different views on the performance of the space; the occupant is the one who will judge the success of the indoor environment. Hence, this idea emphasizes the need for incorporating human agents into such studies for early consideration of human behavior at the design stage. A more complex development for the model may include programming codes for occupants' behavior by research centers, like "Carniege Mellon Robotics Institute"; it is not the only institute that researches this topic, but one of the known ones that has many studies in this area.

This thesis presented an integration of three different tools, Rhino, Grasshopper, and DIVA, used to develop one algorithm that is intended to be used for optimal tilt angle search. The technical difficulties experienced resulted in carrying out manual simulation runs for the search for an optimal scheme. Though some of the simulated schemes showed success at certain times of the year, manual simulation is not an efficient way to find an optimal solution given the infinite possibilities of skin configurations. Solving the DIVA component scripting problem will prove the efficiency of the system in a more reliable and acceptable discussion.

Moreover, intelligent skins are controversial; they may present solutions for better energy-performing architecture, but they cost a lot of money and can be difficult to maintain. If research keeps exploring the performance of these kinds of skins independently without comparing them to feasibility models for cost and development, intelligent skins may not be applicable in the real architecture world. This area requires effort and input from many disciplines other than architecture; among which are business and feasibility, mechanical, electronics, material science, and physics. The integration of inputs from all previous disciplines may result in a system that is cost effective and has a short payback period. However, the architect should be a dominant element in the design process to support new trends in form geometry such as complex geometry and make sure other disciplines are not changing the architecture to make their lives easier. We need to support changing architecture trends rather than narrowing it down to cube and linear geometry only.

BIBLIOGRAPHY

Asefi, Maziar. *Transformable and Kinetic Architectural Structures: Design, Evaluation and Application to Intelligent Architecture*. VDM Verlag Dr. Müller, 2010.

Atkin, Brian. *Intelligent Buildings: Applications of It and Building Automation to High Technology Construction Projects*. Ashgate Publishing, 1993.

Baird, George. *The Architectural Expression of Environmental Control Systems*. Taylor & Francis, 2001.

Baker, Nick V., A. Fanchiotti, and Koen Steemers. *Daylighting in Architecture: A European Reference Book*. Earthscan Publications Ltd., 1993.

Baker, Nick, and Koen Steemers. *Daylight Design of Buildings*. Annotated edition. Earthscan Publications Ltd., 2002.

Becker, Eike. *Headquarters Building of Verbundnetz Gas Ag Leipzig*. Illustrated edition. Prestel Publishing, 2000.

Bernaden, John A. *The Intelligent Building Sourcebook*. Prentice Hall, 1988.

Boubekri, Mohamed. *Daylighting, Architecture and Health: Building Design Strategies*. Architectural Press, 2008.

Bradshaw, Vaughn. *The Building Environment: Active and Passive Control Systems*. 3rd ed. Wiley, 2006.

Brambley, M.R., P. Haves, and S.C. McDonald. *Advanced Sensors and Controls for Building Applications: Market Assessment and Potential R&D Pathways*, April 2005. http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/pnnl-15149_market_assessment.pdf.

"Brise soleil - Wikipedia, the free encyclopedia", n.d. http://en.wikipedia.org/wiki/Brise_soleil.

California Energy Commission. *Daylight Harvesting Made Simple*. California, USA, September 2008. http://www.esource.com/esource/getpub/public/pdf/cec/CEC-TB-36_Daylighting.pdf.

Carlson, Reinhold A., and Robert A. DiGiandomenico. *Understanding Building Automation Systems*. R.S. Means Company, Inc., 1991.

Clements-Croome, Professor Derek. *Intelligent Buildings: Design Management and Operation*. Thomas Telford Publishing, 2004.

Compagno, Andrea. *Intelligente Glasfassaden / Intelligent Glass Façades: Material, Anwendung, Gestaltung / Material, Practice, Design*. 5th ed. Birkhäuser Basel, 2002.

"Curtain wall - Wikipedia, the free encyclopedia", n.d. http://en.wikipedia.org/wiki/Curtain_wall.

Dasgupta, Ujjaini. *The Impact of Windows on Mood and Performance of Judgmental Tasks*. Rensselaer Polytechnic Institute, 2003.

DiLouie, Craig. *Advanced lighting controls: energy savings, productivity, technology and applications*. The Fairmont Press, Inc., 2006.

"DIVA for Rhino - Credits", n.d. http://www.diva-for-rhino.com/credits.html.

"DIVA for Rhino Website", 2011. http://www.diva-for-rhino.com/.

"D-LITE: Database of Light-Interacting Technologies for Envelopes." *D-LITE ABOUT*, n.d. http://www.d-lite.org/.

Dubois, Marie-Claude. "Impact of Solar Shading Devices on Daylight Quality: Measurements in Experimental Office". Sweden: Lund University, 2001. http://www.grap.arc.ulaval.ca/attaches/Dubois/BOK-3061.PDF.

Edwards, Brian. *Green Buildings Pay*. 2nd ed. Taylor & Francis, 2003.

Encelium Technologies. "Lighting Energy Management System: Six Smart Strategies", n.d. www.encelium.com.

Fathy, Hassan. *Natural Energy and Vernacular Architecture: Principles and Examples with Reference to Hot Arid Climates*. University Of Chicago Press, 1986.

Flagge, Ingeborg, Verena Herzog-Loibl, and Anna Meseure. *Thomas Herzog: Architecture and Technology*. Bilingual. Prestel, 2002.

"FLARE-facade", n.d. http://www.flare-facade.com/.

Fontoynont, Marc. *Daylight Performance of Buildings*. Illustrated edition. Earthscan Publications Ltd., 1999.

Fox, Michael, and Miles Kemp. *Interactive Architecture*. 1st ed. Princeton Architectural Press, 2009.

Galasiu, A.D., G.R. Newsham, C. Suvagau, and D.M. Sander. “Energy saving lighting control systems for open-plan offices: a field study.” *Leukos* 4, no. 1 (July 1, 2007): 7-29.

Government of Canada. National Research Council Canada. Institute for Research in Construction. “Daylight-linked Lighting Control Systems - Projects - NRC-CNRC”, n.d. http://www.nrc-cnrc.gc.ca/eng/projects/irc/daylighting.html.

Grimmer, D.P., K.G. Zinn, K.C. Herr, and B.E. Wood. “Augmented solar energy collection using different types of planar reflective surfaces; theoretical calculations and experimental results.” *Solar Energy* 21, no. 6 (1978): 497-501.

Guzowski, Mary. *Daylighting for Sustainable Design*. 1st ed. McGraw-Hill Professional, 1999.

Hansanuwat, Ryan. “Kinetic facades as environmental control systems: using kinetic facades to increase energy efficiency and building performance in office buildings”, 2010.

Hauer, Erwin. *Erwin Hauer: Continua-Architectural Screen and Walls*. Princeton Architectural Press, 2007.

Hensel, Michael, Achim Menges, and Michael Weinstock. *Emergent Technologies and Design: Towards a Biological Paradigm for Architecture*. Routledge, 2010.

Hindrichs, Dirk U., and Winfried Heusler. *Fassaden / Façades: Gebäudehüllen für das 21. Jahrhundert / Building Envelopes for the 21st Century*. 2nd ed. Birkhäuser (Princeton Architectural Press), 2005.

Howlett, O., C. Eaton, R. Raghavan, and R. P. Leslie. “The potential of simplified concepts for daylight harvesting.” *Lighting Research & Technology* 37, no. 1 (March 1, 2005): 21-38.

Hu, Jia, and Svetlana Olbina. “Illuminance-based Slat Angle Selection Model for Automated Control of Split Blinds.” *Building and Environment* (October 20, 2010).

Hunter, C M, C C Jones, P R Boyce, M. Myer, J A Veitch, J. Heerwagen, and G R Newsham. “Occupant use of switching and dimming controls in offices.” *Lighting Research & Technology* 38, no. 4 (December 1, 2006): 358-376.

"iBuilding Website", n.d. http://www.ibuilding.gr/definitions.html.

IES North America. *IESNA Lighting Handbook*. 9th ed. Illuminating Engineering Society of North Ame, 2000.

"Improving the Energy Performance of Buildings." Product Page, 2009. http://www.rand.org/pubs/technical_reports/TR728.html.

ISO/CIE. *ISO/CIE 8995-1:2002, Lighting of indoor work places - Part 1: Indoor*. Multiple. Distributed through American National Standards Institute (ANSI), 2007.

Kenzari, Bechir, and Yasser Elsheshtawy. "The Ambiguous Veil: On Transparency, the Mashrabiy'ya, and Architecture." *Journal of Architectural Education* 56, no. 4 (2003): 17-25.

Knaack, Ulrich, Tillmann Klein, Marcel Bilow, and Thomas Auer. *Facades: Principles of Construction*. 1st ed. Birkhäuser Architecture, 2007.

Koster, Helmut. *Dynamic Daylighting Architecture: Basics, Systems, Projects*. Springer Verlag, 2004.

Kronenburg, Robert. *Portable Architecture: Design and Technology*. 1st ed. Birkhäuser Architecture, 2008.

Kwok, Alison, and Walter Grondzik. *The Green Studio Handbook: Environmental Strategies for Schematic Design*. 1st ed. Architectural Press, 2006.

Lechner, Norbert. *Heating, Cooling, Lighting: Sustainable Design Methods for Architects*. 3rd ed. Wiley, 2008.

Lee, E.S., and S.E. Selkowitz. "The New York Times Headquarters daylighting mockup: Monitored performance of the daylighting control system." *Energy and Buildings* 38, no. 7 (July 2006): 914-929.

"Lighting Control System - Encelium's Energy Control System (ECS)", n.d. http://www.encelium.com/.

"Liverpool Architecture", n.d. http://www.liverpoolarchitecture.com/tours/buildings/building.php?id=25.

Lovell, Jenny. *Building Envelopes: An Integrated Approach*. Princeton Architectural Press, 2010.

Marmot, Alexi, and Joanna Eley. *Office space planning: designing for tomorrow's workplace*. McGraw-Hill Professional, 2000.

"Mashrabiya - Wikipedia, the free encyclopedia", n.d. http://en.wikipedia.org/wiki/Mashrabiya.

McDonough, William, and Michael Braungart. *Cradle to Cradle: Remaking the Way We Make Things*. 1st ed. North Point Press, 2002.

McGuire, Molly E. "A system for optimizing interior daylight distribution using reflective Venetian blinds with independent blind angle control". Massachusetts Institute of Technology, 2005.

Melendo, Jose Manuel Almodovar, Jose Maria Cabeza Lainez, and Juan Ramon Jimenez Verdejo. "Nineteen Thirties Architecture for Tropical Countries: Le Corbusier′s Brise–Soleil at the Ministry of Education in Rio de Janeiro." *Journal of Asian Architecture and Building Engineering* 7, no. 1 (2008): 9-14.

Michael, Simms, and Gerber David. "SOM + SCI-Arc on CF:Responsive Kinetic Facade", n.d. http://www.core.form-ula.com/2009/04/15/som-sci-arc-on-cfresponsive-kinetic-facade/.

Moloney, Jules. "Building Skins as Kinetic Process: Some Precedent from the Fine Arts". Sydney, Australia, 2007. http://hdl.handle.net/2100/484.

Moore, T. "Harvesting daylight inside buildings." *EPRI JOURNAL* 23, no. 4 (July 1, 1998): 18-25.

Murray, Scott. *Contemporary Curtain Wall Architecture*. 1st ed. Princeton Architectural Press, 2009.

National Research Council Canada. "Lighting Design for Open-Plan Offices", n.d. http://www.nrc-cnrc.gc.ca/eng/ibp/irc/ctus/ctus-n62.html.

Nixon, Paddy, Gerard Lacey, Simon Dobson, and University of Dublin Trinity College. *Managing Interactions in Smart Environments*. Springer, 2000.

O'Connor, Jennifer. *Tips for daylighting with windows: the integrated approach*. Ernest Orlando Lawrence Berkeley National Laboratory, 1997. http://windows.lbl.gov/daylighting/designguide/dlg.pdf.

O'Neill, Brendan. "Model-based control of venetian blinds", 2008.

"People Image Analysis (PIA) Consortium, Carnegie Mellon Robotics Institute", n.d. http://www.consortium.ri.cmu.edu/.

Petersen, Marianne Graves. "Interactive spaces: towards a better everyday?" *interactions*, July 2005.

Phillips, Derek. *Daylighting: Natural Light in Architecture*. 1st ed. Architectural Press, 2004.

"Radiance rpict program", n.d. http://radsite.lbl.gov/radiance/man_html/rpict.1.html.

Reinhart, C., and P. F. Breton. "Experimental Validation of Autodesk (R) 3ds Max (R) Design 2009 and Daysim 3.0." *LEUKOS* 6, no. 1 (July 1, 2009): 7-35.

"Robotics Institute: Agent-based Composition of Behavioral Models", n.d. http://www.ri.cmu.edu/research_project_detail.html?project_id=551&menu_id=261.

Rosenfeld, Arthur H., and Stephen E. Selkowitz. "Beam daylighting: an alternative illumination technique." *Energy and Buildings* 1, no. 1 (May 1977): 43-50.

Santamouris, Mat. *Advances in Building Energy Research: Volume 2*. Earthscan Publications Ltd., 2008.

Sauerbruch, Matthias, Louisa Hutton, Isabelle Hartmann, and Sauerbruch Hutton Architekten. *GSW Headquarters Berlin: Sauerbruch Hutton Architects*. 1st ed. Lars Müller Publishers, 2000.

Schiler, Marc. *Simplified Design of Building Lighting*. Wiley-Interscience, 1992.

Schiler, Marc(first). *Daylight Harvesting*. Southern California Gas Company, 1995.

Schmalzel, J., F. Figueroa, J. Morris, S. Mandayam, and R. Polikar. "An Architecture for Intelligent Systems Based on Smart Sensors." *IEEE Transactions on Instrumentation and Measurement* 54, no. 4 (2005): 1612-1616.

"Sennari House In Cairo: Home to Napoleon's Scholars", n.d. http://www.touregypt.net/featurestories/sennarihouse.htm.

Soldner, J. G. v, J. G. v. "On the deflection of a light ray from its rectilinear motion, by the attraction of a celestial body at which it nearly passes by." *Berliner Astronomisches Jahrbuch* (1804): 161–172.

"The light side of gravity — Einstein Online", n.d. http://www.einstein-online.info/elementary/generalRT/Light_deflection.

"Thiele AG - Transparente Innovation", n.d. http://www.thiele-ag.de/en/management.html.

Tregenza, Peter, and Michael Wilson. *Daylighting: Architecture and Lighting Design*. 1st ed. Routledge, 2011.

Trumpler, R. J. "The Relativity Deflection of Light." *Publications of the Astronomical Society of the Pacific* 41 (February 1, 1929): 23.

Veitch, J. A. "Psychological processes influencing lighting quality." *Journal of the Illuminating Engineering Society* 30, no. 1 (April 1, 2001): 124.

Veitch, J.A. *Determinants of Lighting Quality I: State of the Science - NRC-IRC*. Cleveland, OH: Annual Conference of the Illuminating Engineering Society of North America, n.d. http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/nrcc39866.php.

Wang, Shengwei. *Intelligent Buildings and Building Automation*. T & F Books UK, 2009.

"Weather Today - Weather Forecasts, Radar, Maps for 1000s of US and World Cities", n.d. http://www.weathertoday.net/weatherfacts/numbersunny_bycity.php.

Wigginton, Michael, and Jude Harris. *Intelligent Skins*. Architectural Press, 2002.

APPENDIX A: **ILLUMINANCE NODE POINT RESULTS**

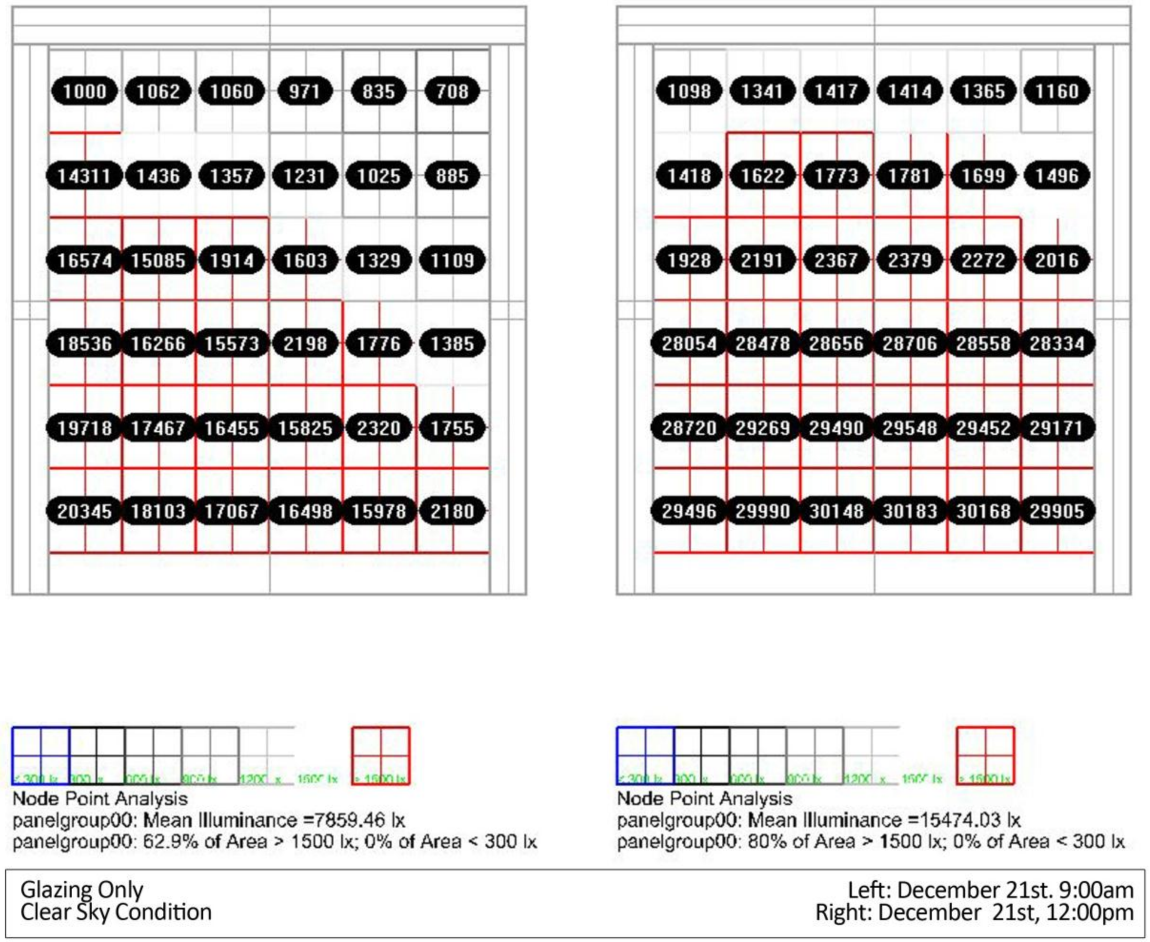


Figure 9-1: Glazing only results - The figure shows the illuminance node values inside the space.

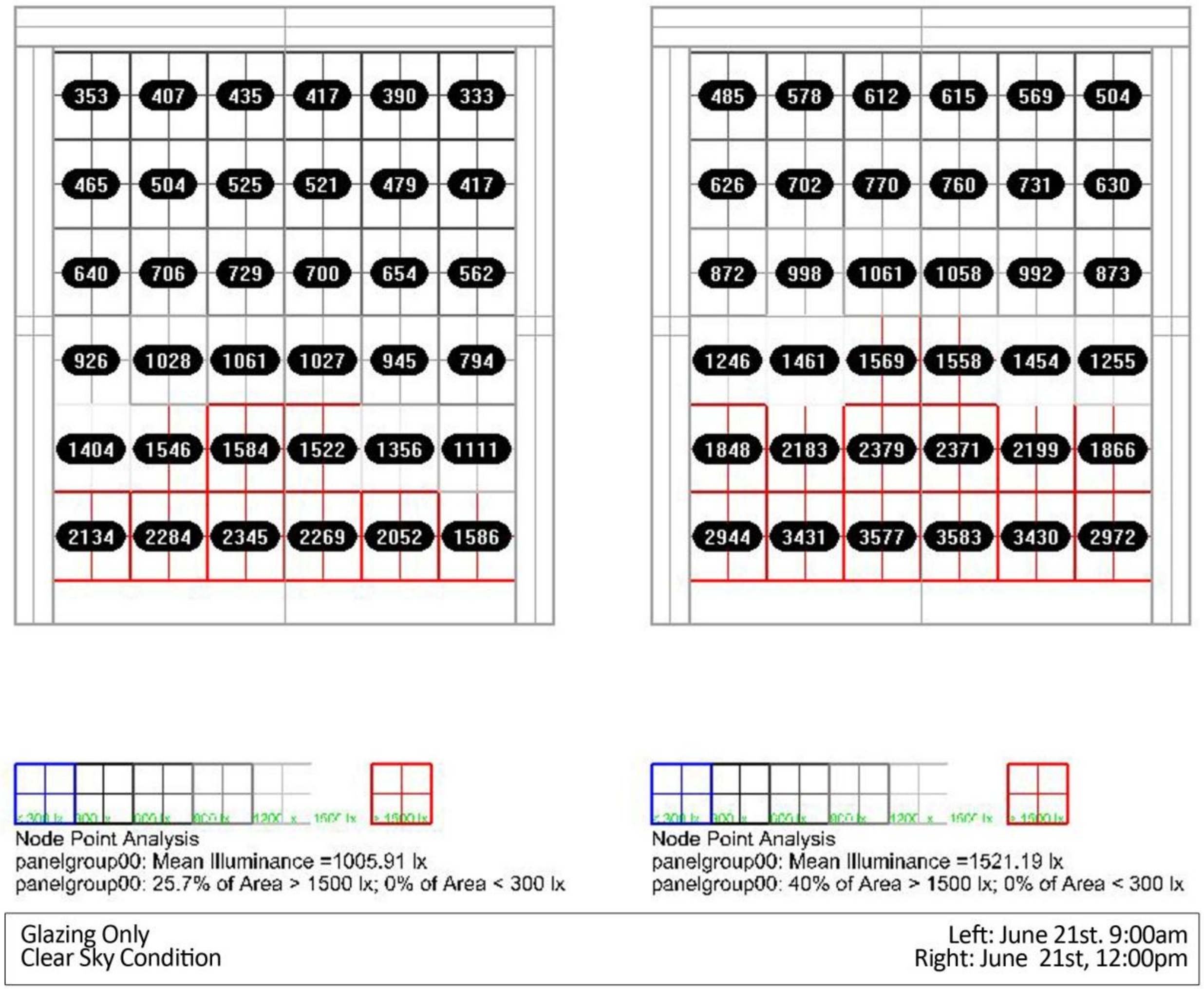


Figure 9-2: Glazing only results - The figure shows the illuminance node values inside the space.

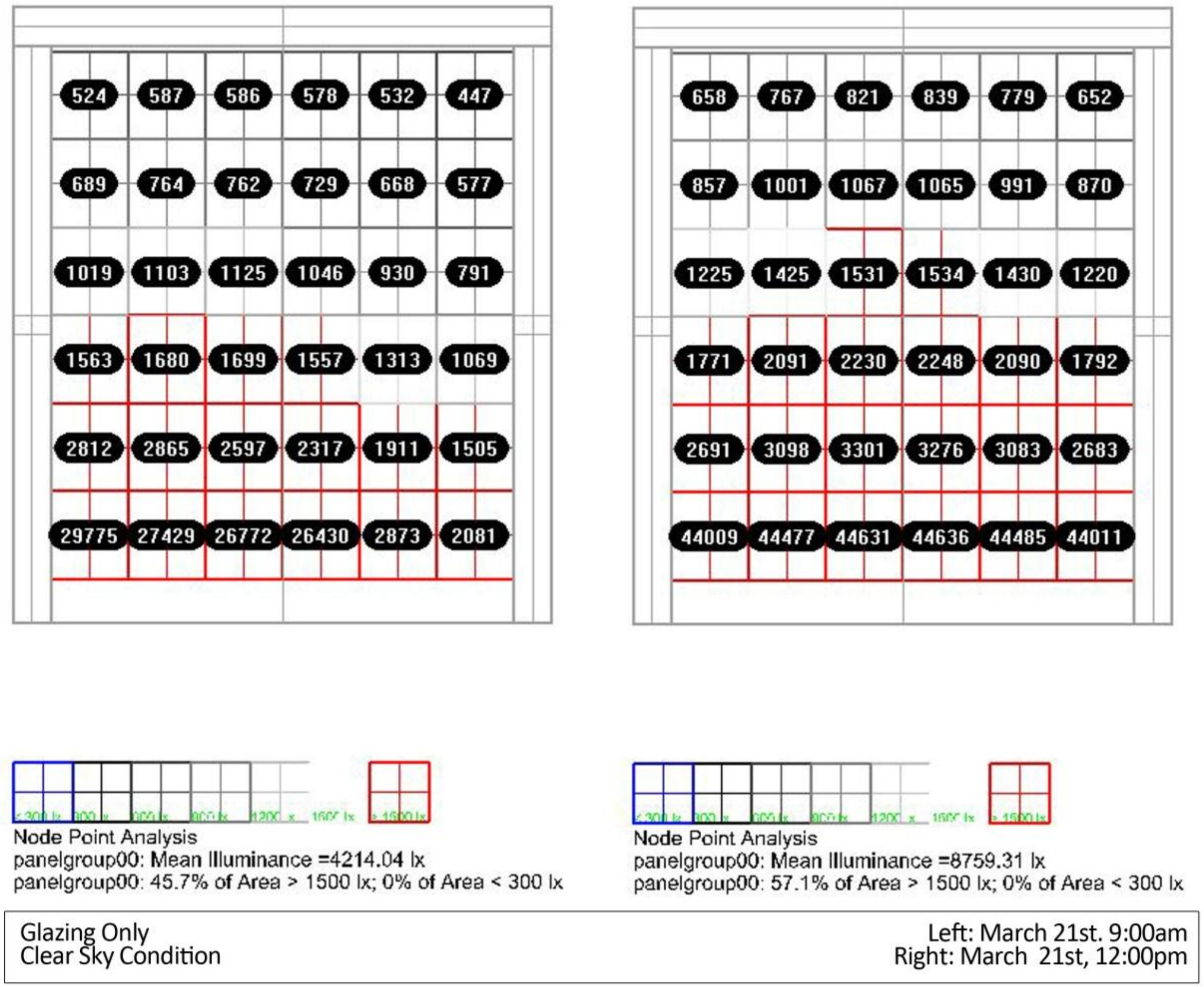


Figure 9-3: Glazing only results - The figure shows the illuminance node values inside the space.

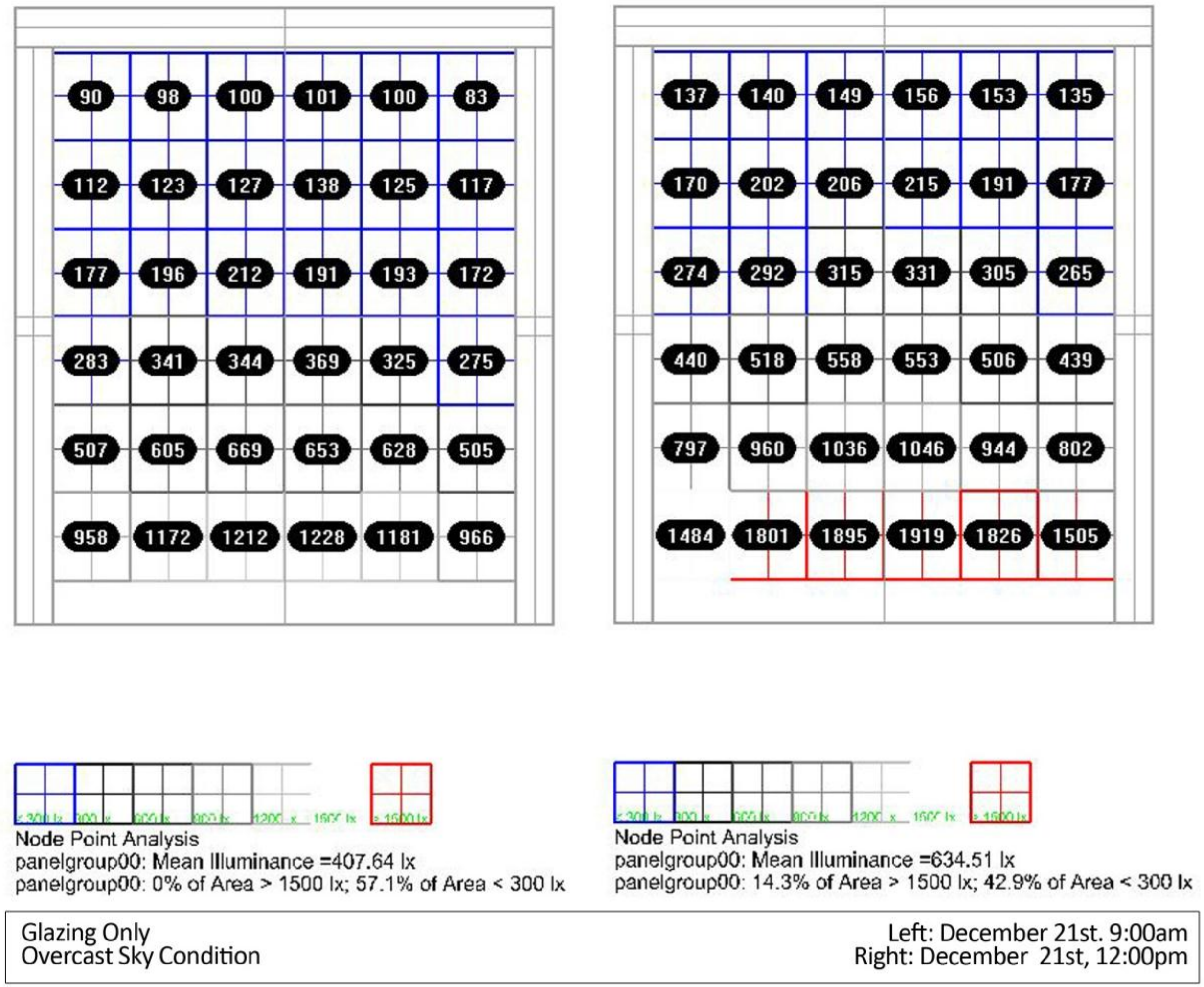


Figure 9-4: Glazing only results - The figure shows the illuminance node values inside the space.

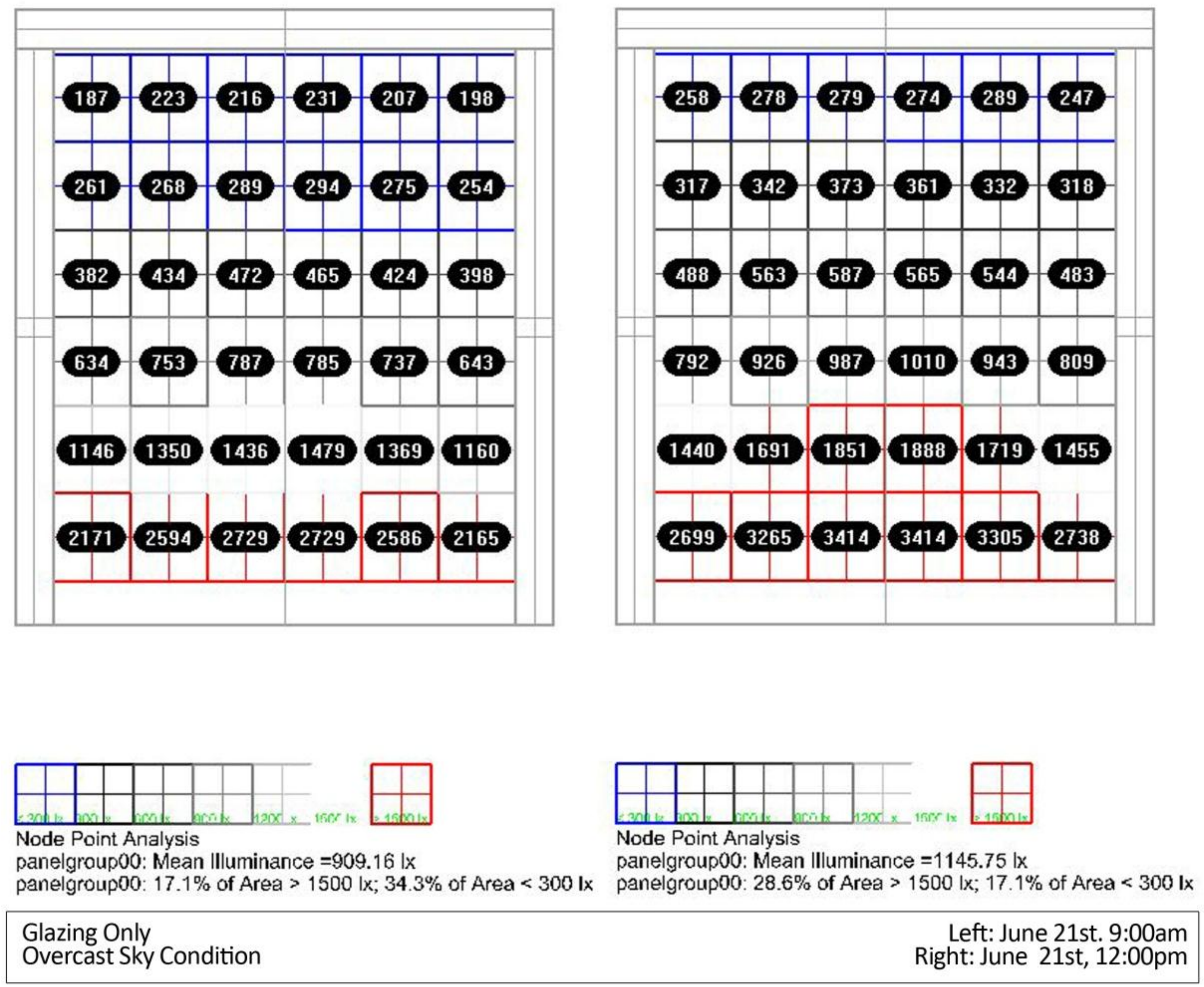


Figure 9-5: Glazing only results - The figure shows the illuminance node values inside the space.

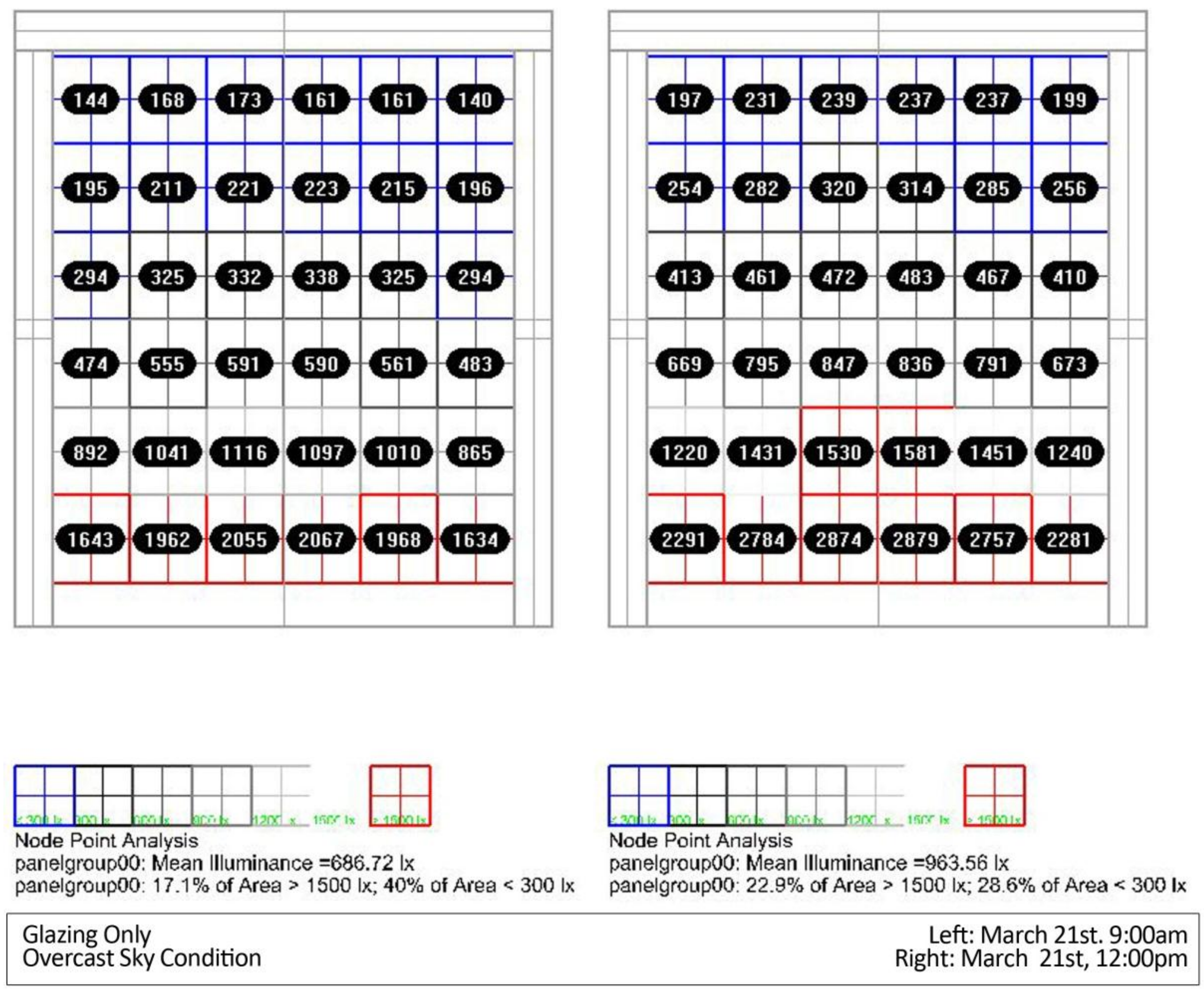


Figure 9-6: Glazing only results - The figure shows the illuminance node values inside the space.

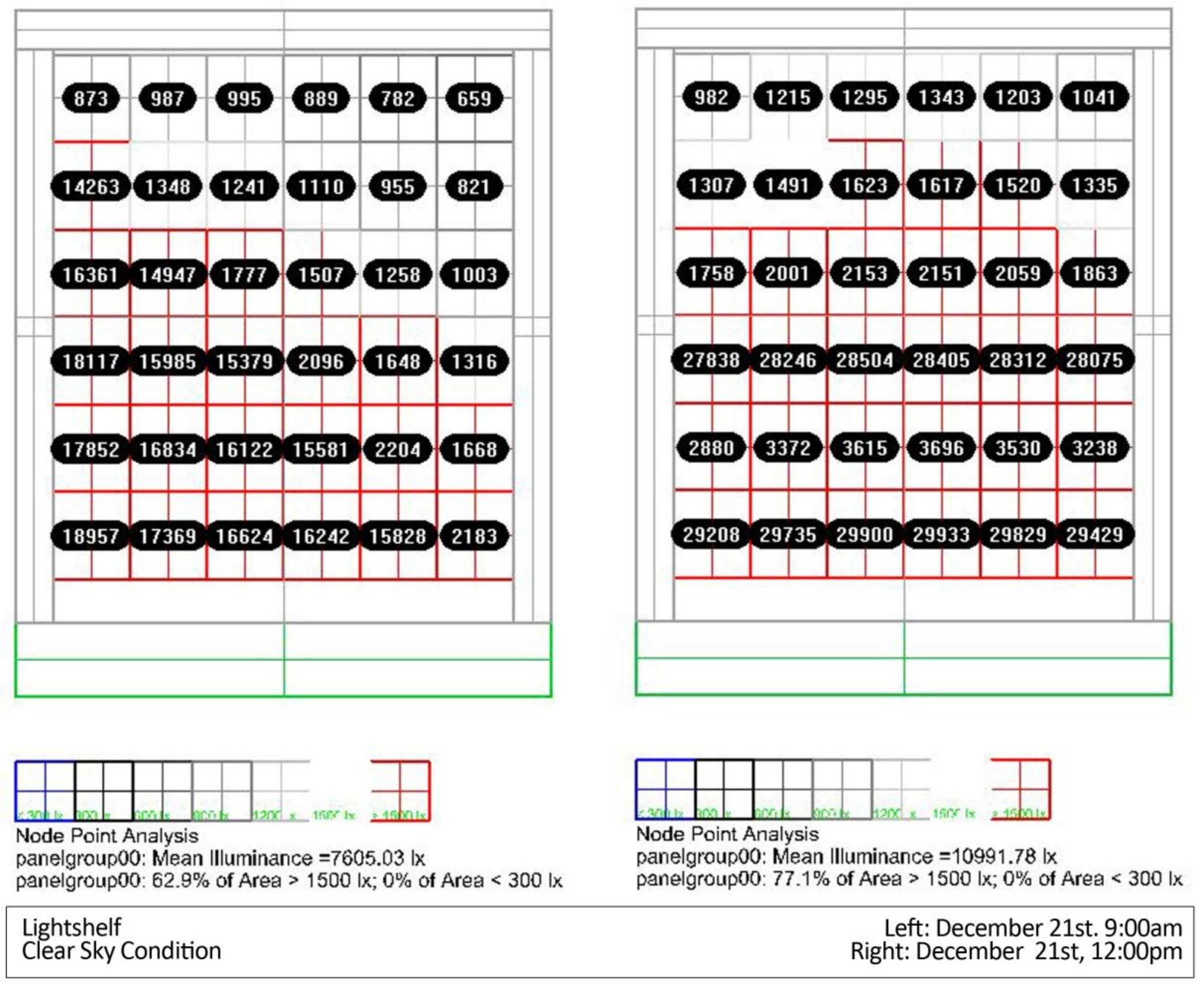


Figure 9-7: Lightshelf results - The figure shows the illuminance node values inside the space.

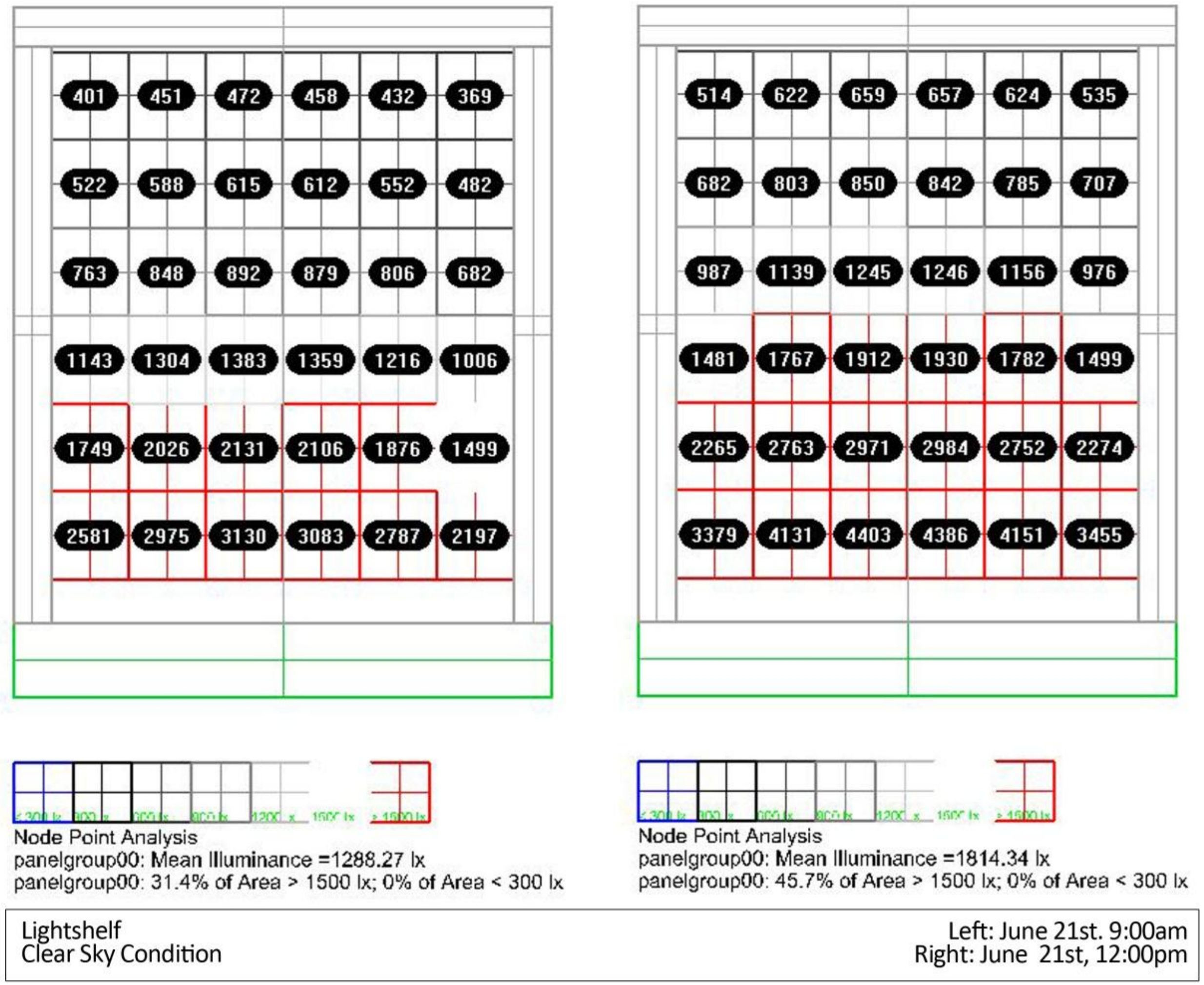


Figure 9-8: Lightshelf results - The figure shows the illuminance node values inside the space.

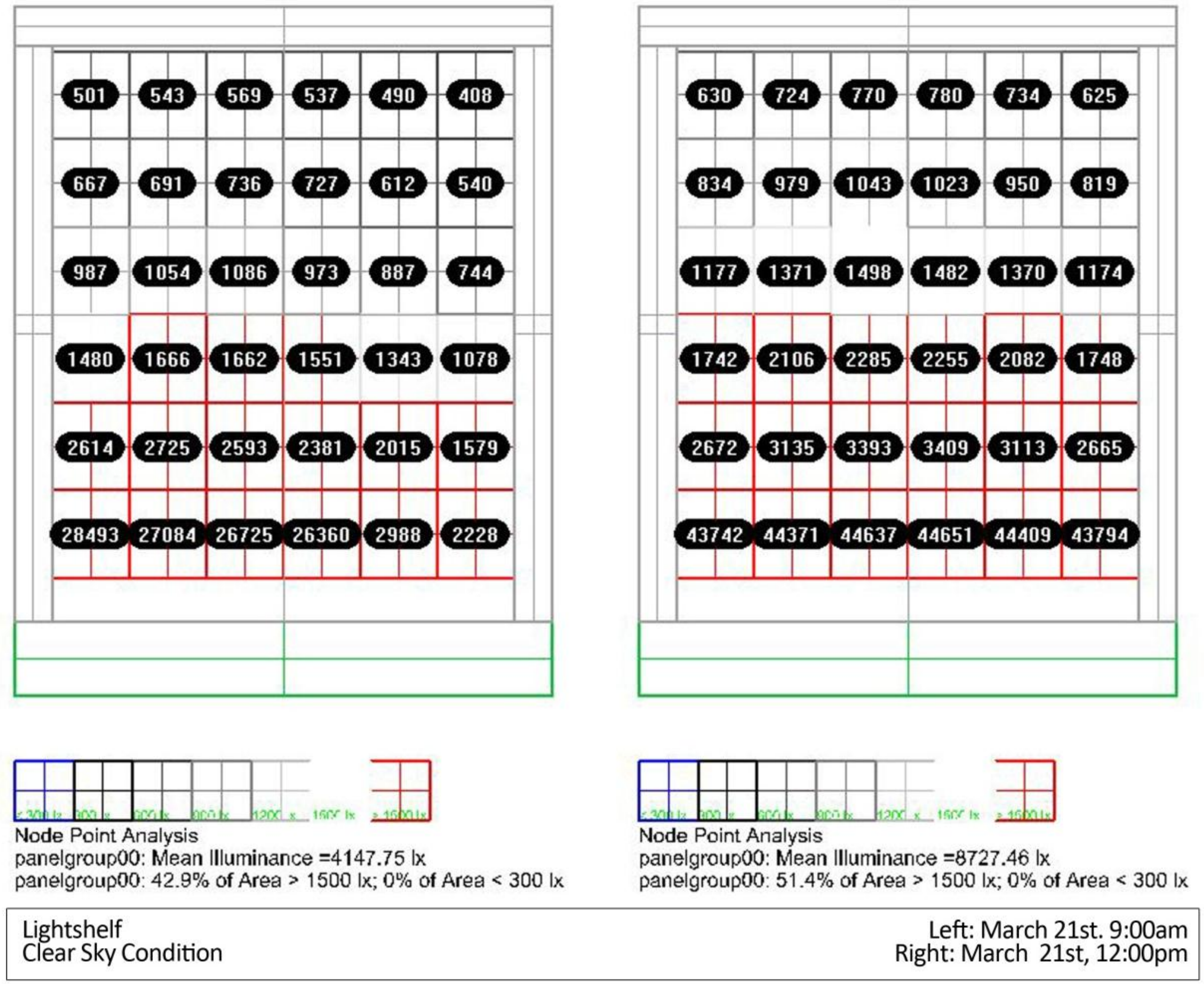


Figure 9-9: Lightshelf results - The figure shows the illuminance node values inside the space.

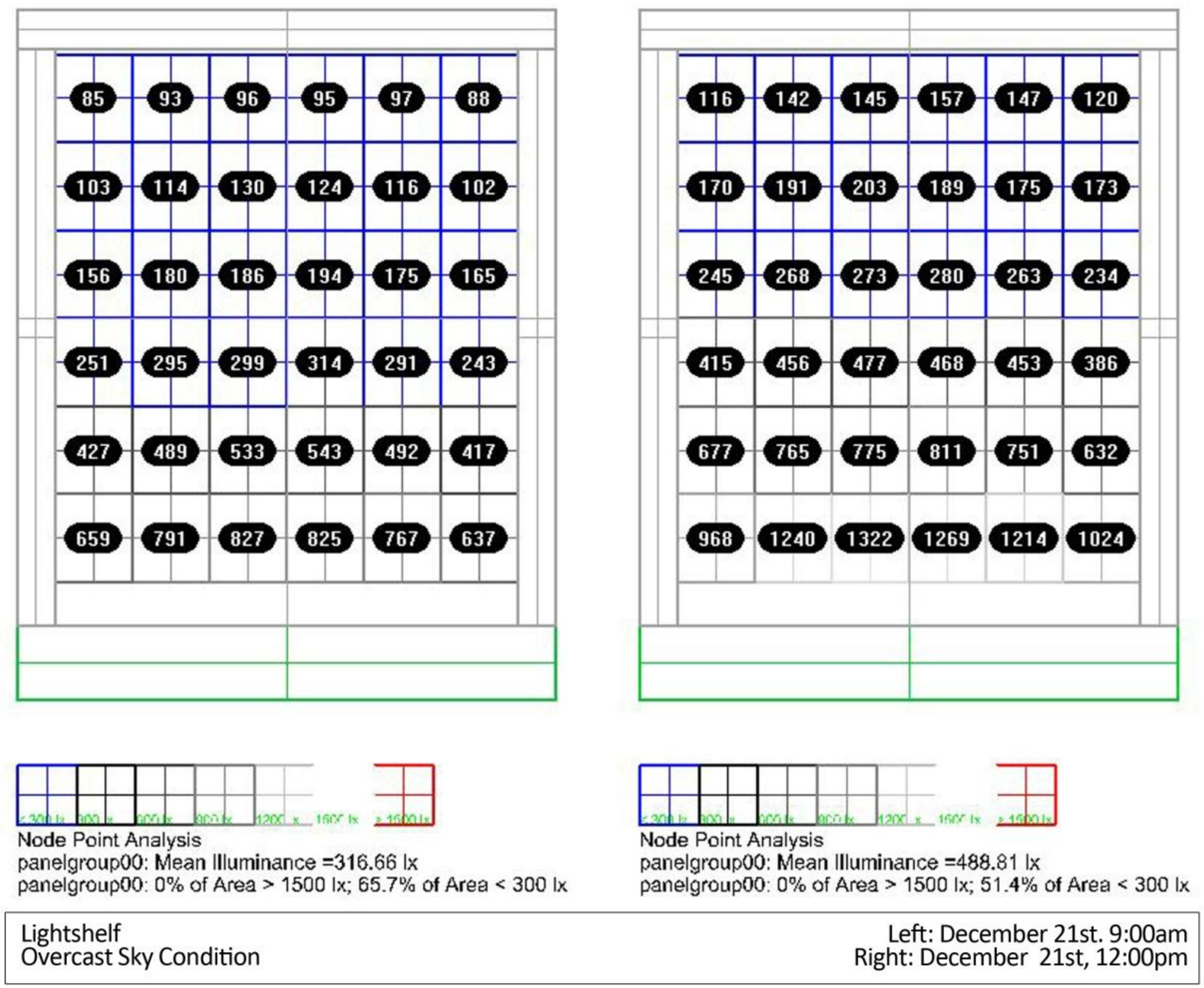


Figure 9-10: Lightshelf results - The figure shows the illuminance node values inside the space.

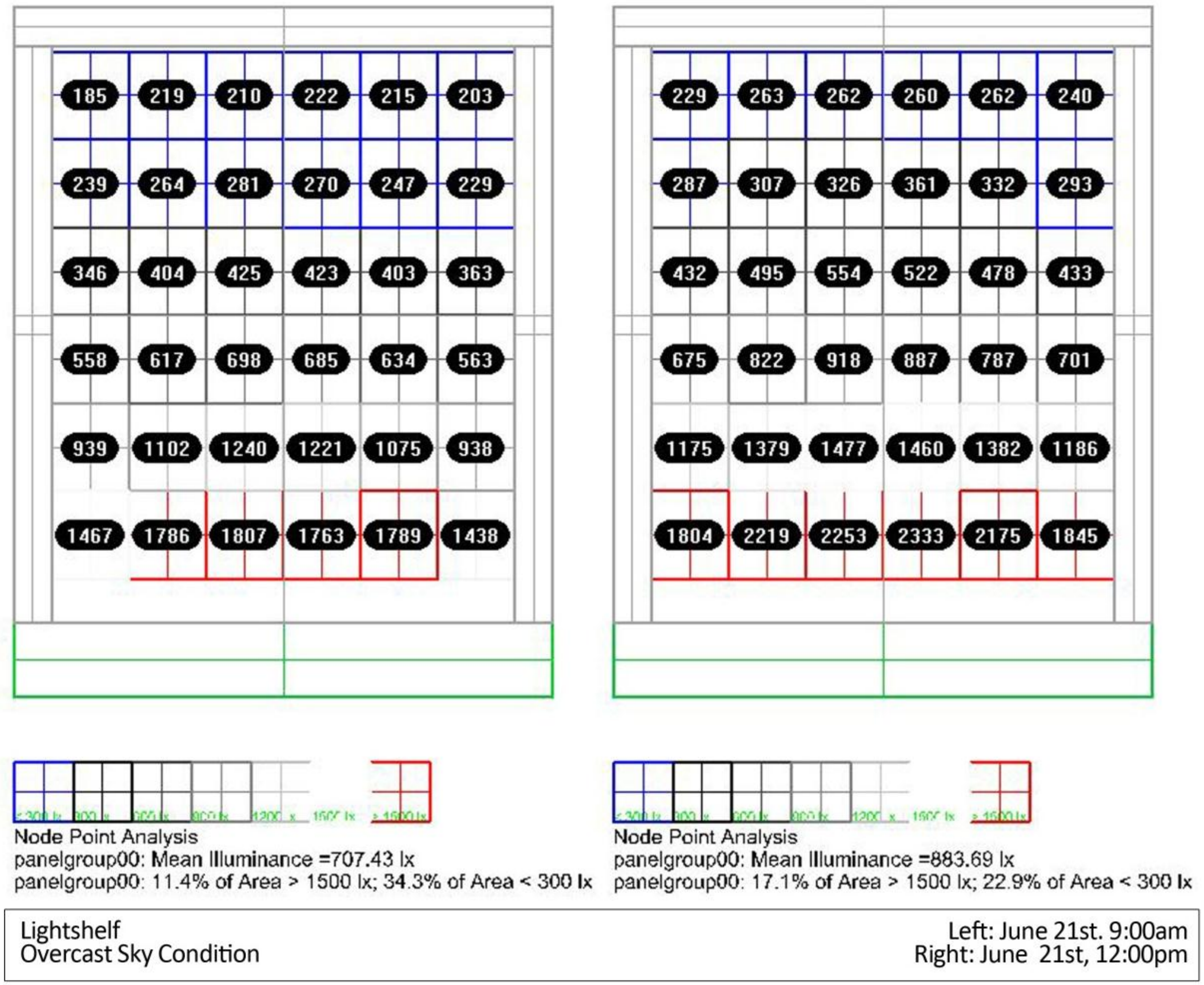


Figure 9-11: Lightshelf results - The figure shows the illuminance node values inside the space.

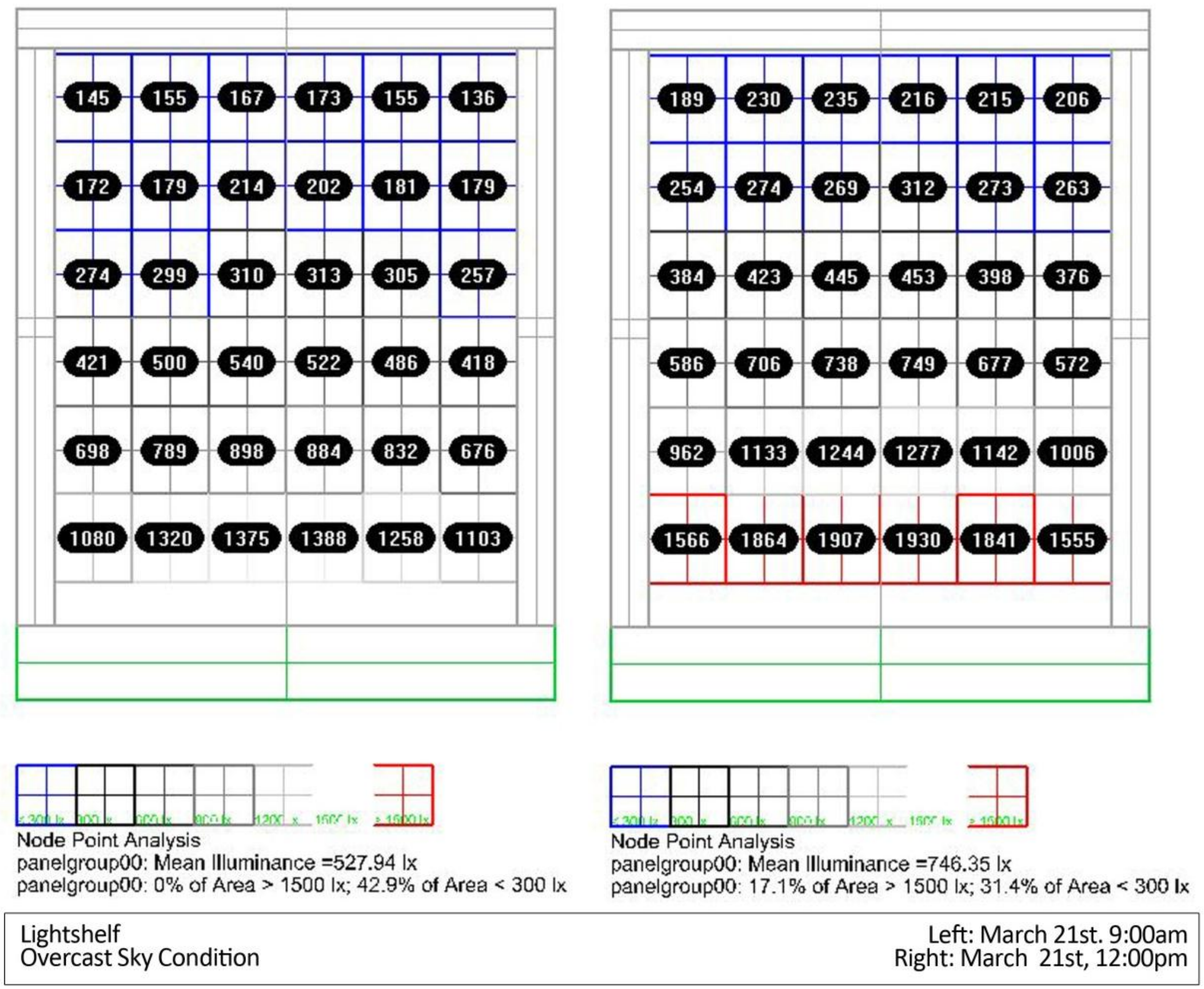
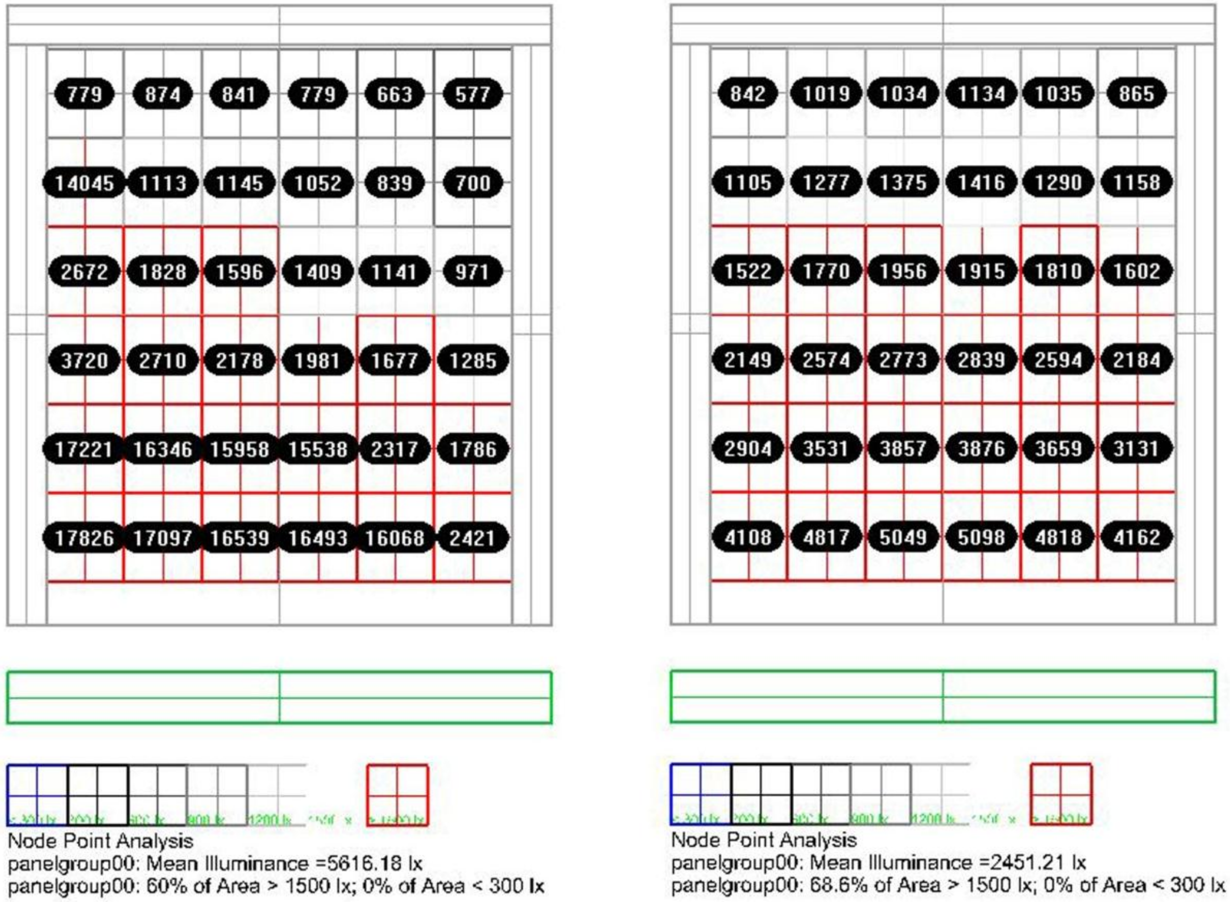


Figure 9-12: Lightshelf results - The figure shows the illuminance node values inside the space.



Horizontal Louvers Clear Sky Condition	Left: December 21st. 9:00am Right: December 21st, 12:00pm

Figure 9-13: Horizontal louvers results - The figure shows the illuminance node values inside the space.

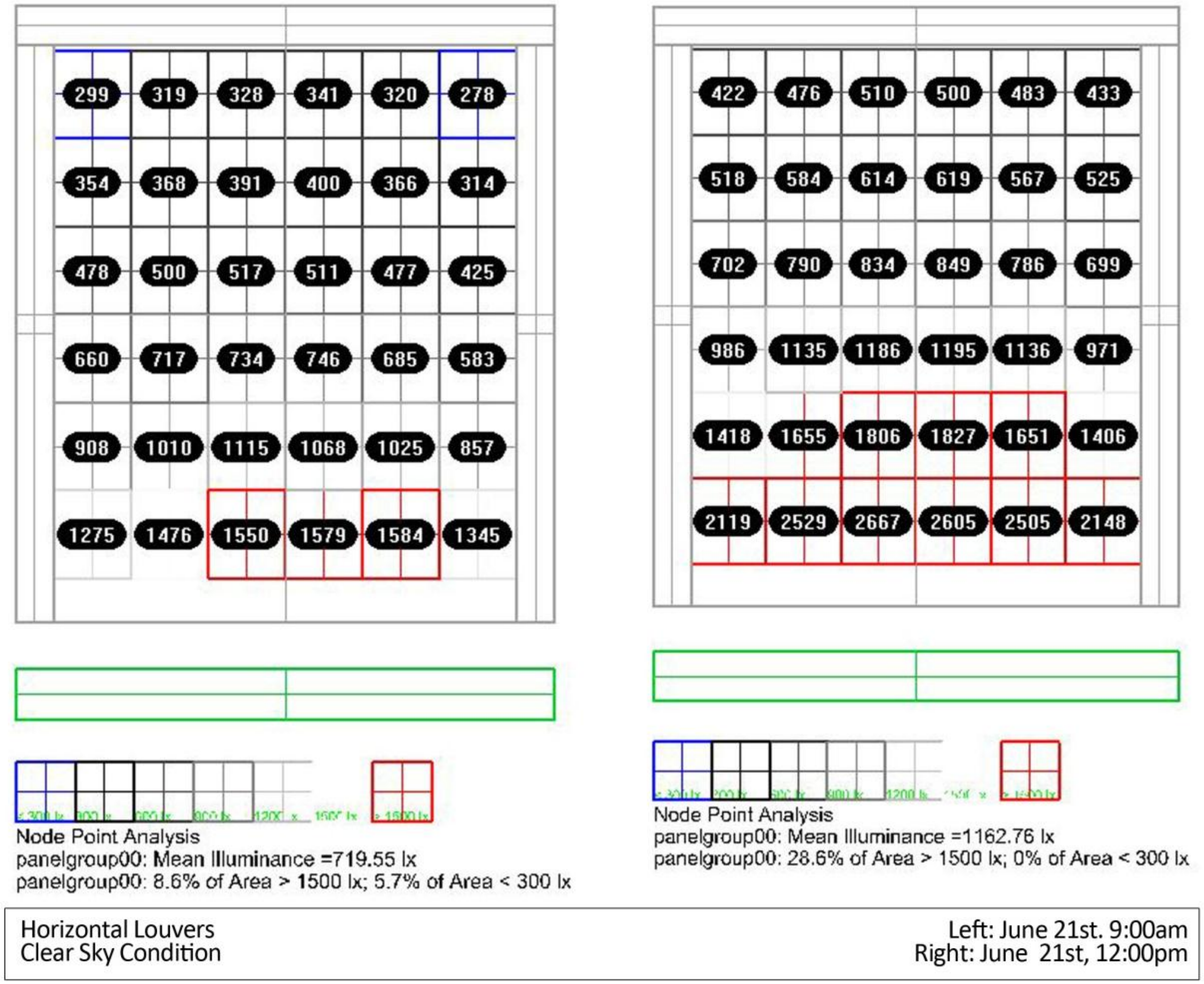


Figure 9-14: Horizontal louvers results - The figure shows the illuminance node values inside the space.

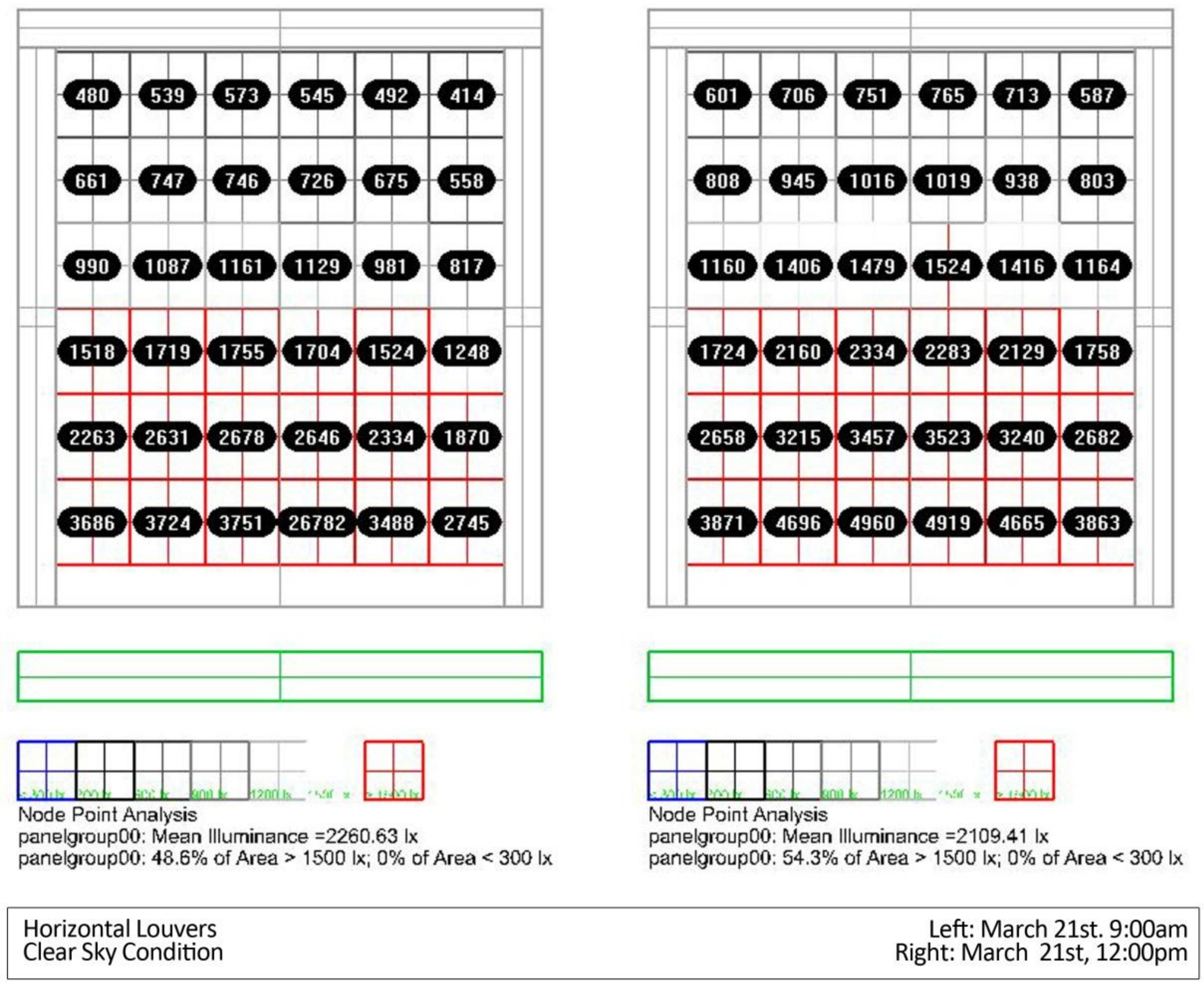


Figure 9-15: Horizontal louvers results - The figure shows the illuminance node values inside the space.

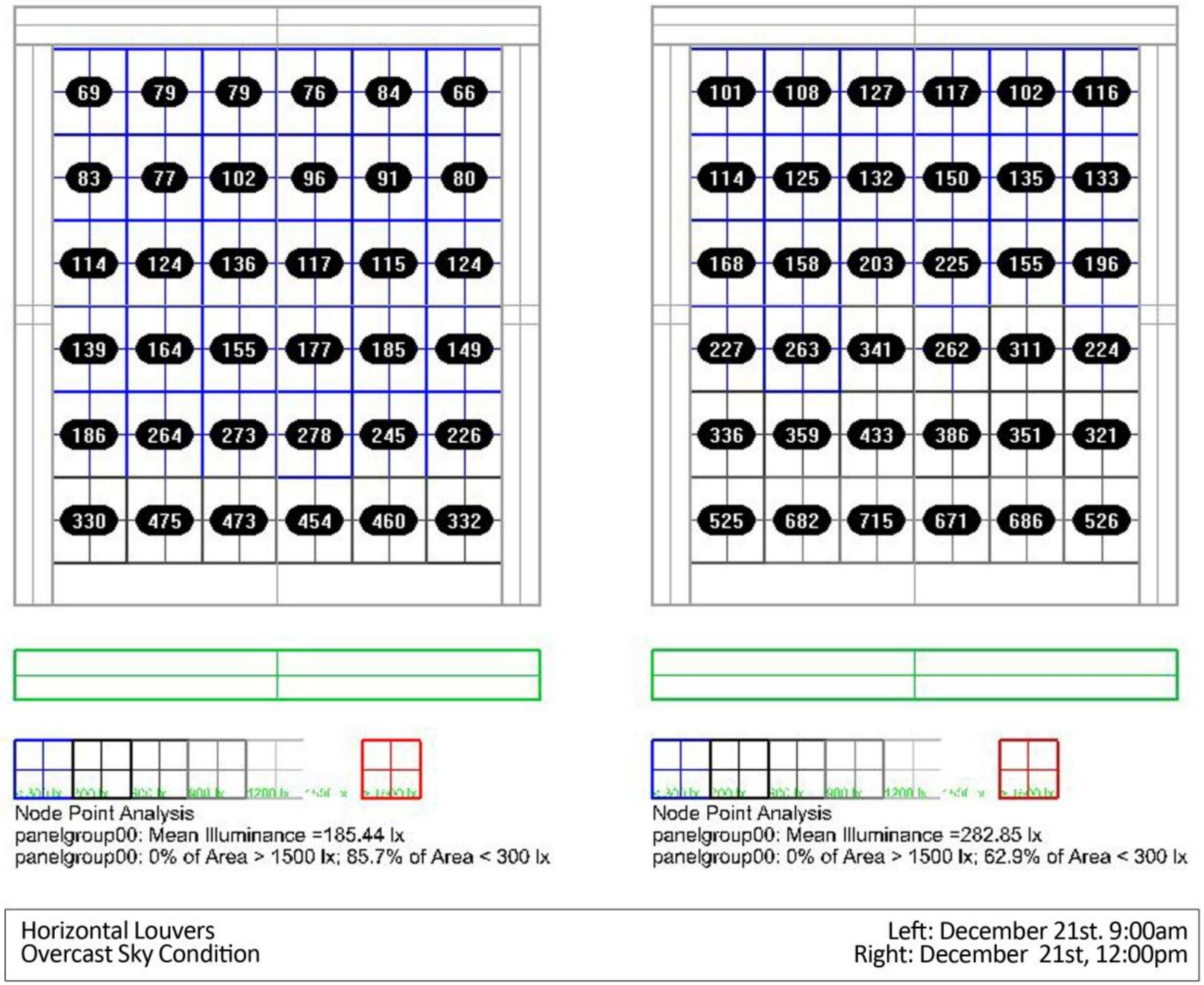


Figure 9-16: Horizontal louvers results - The figure shows the illuminance node values inside the space.

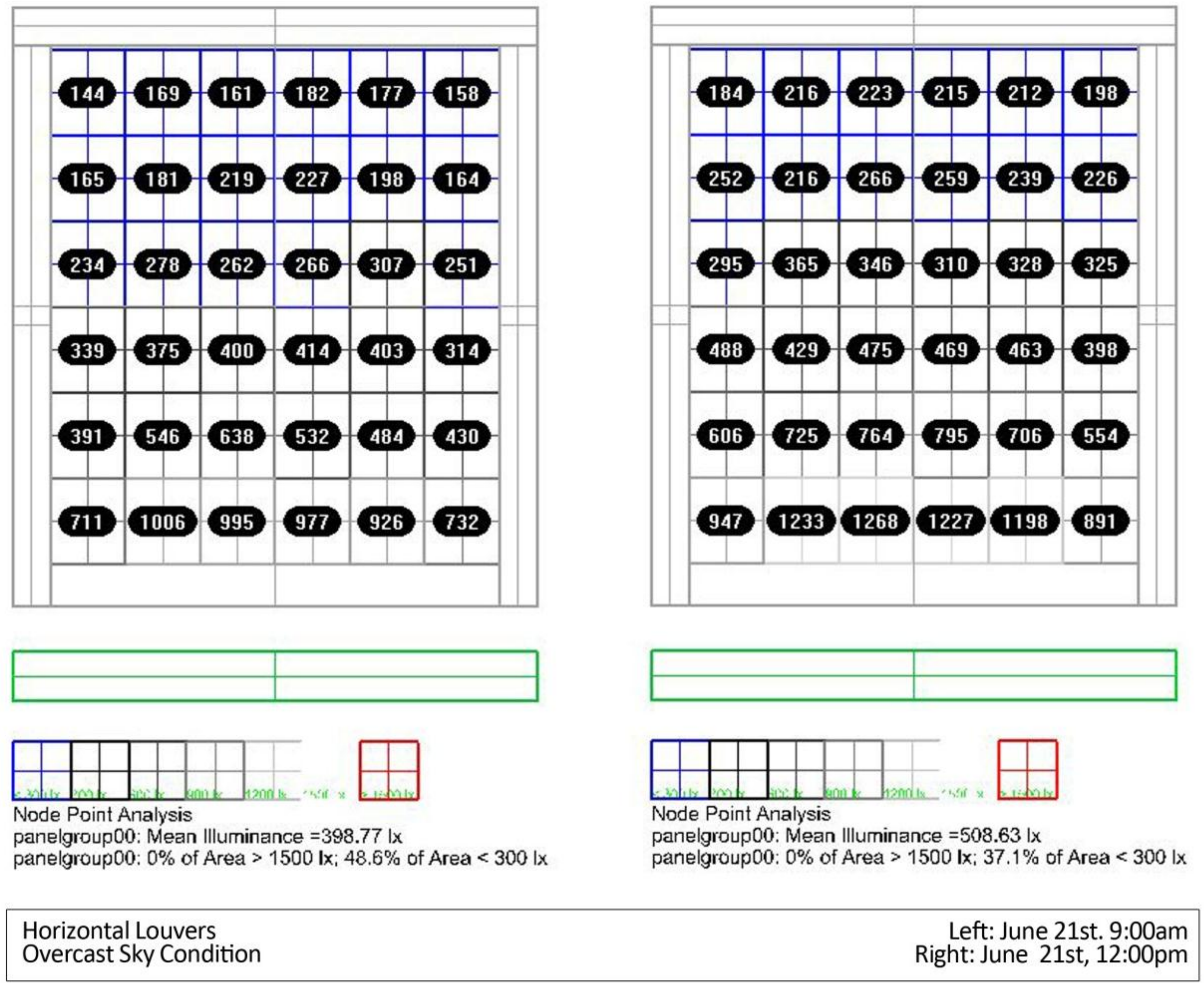


Figure 9-17: Horizontal louvers results - The figure shows the illuminance node values inside the space.

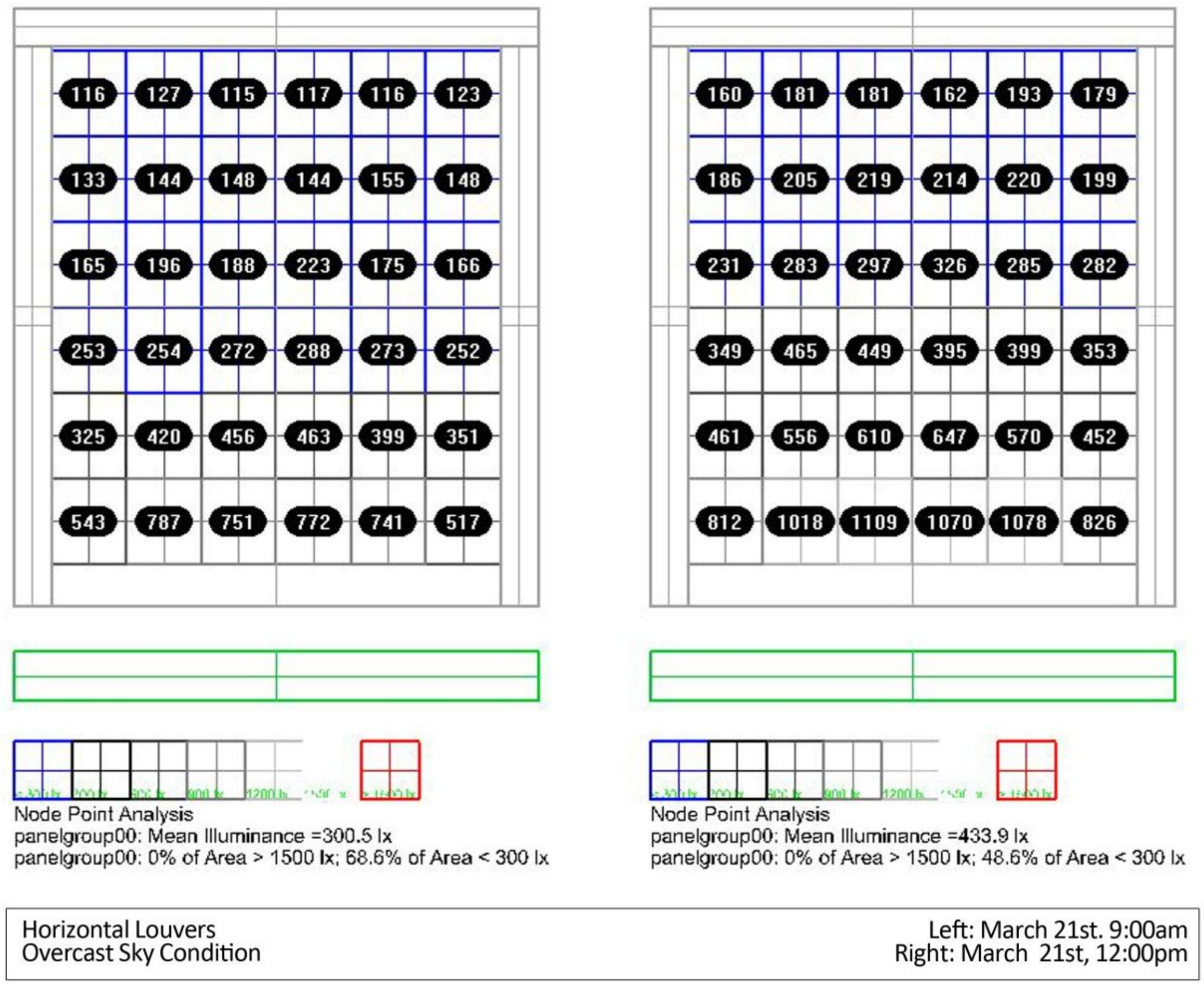


Figure 9-18: Horizontal louvers results - The figure shows the illuminance node values inside the space.

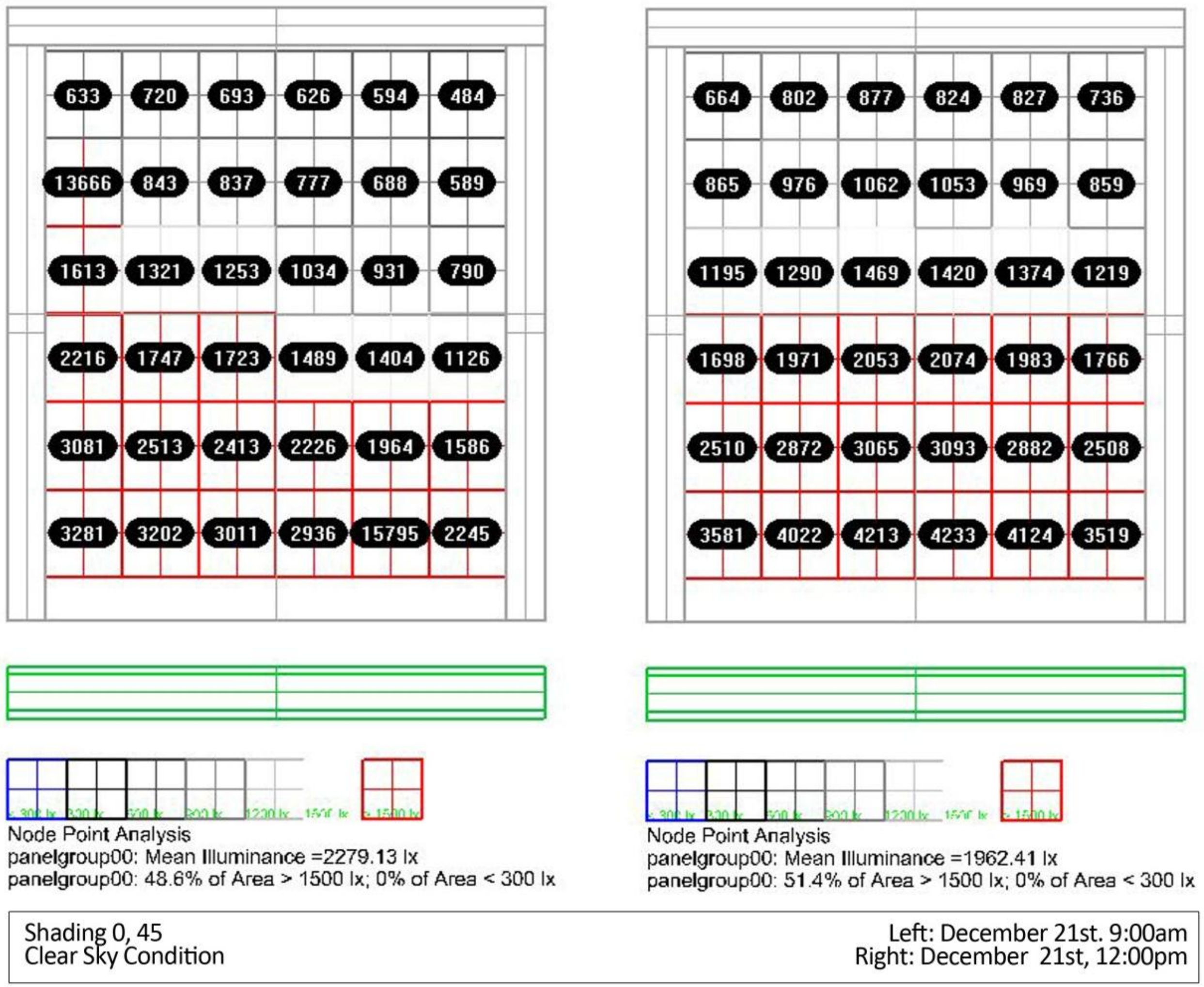


Figure 9-19: Shading 0° and 45° results - The figure shows the illuminance node values inside the space.

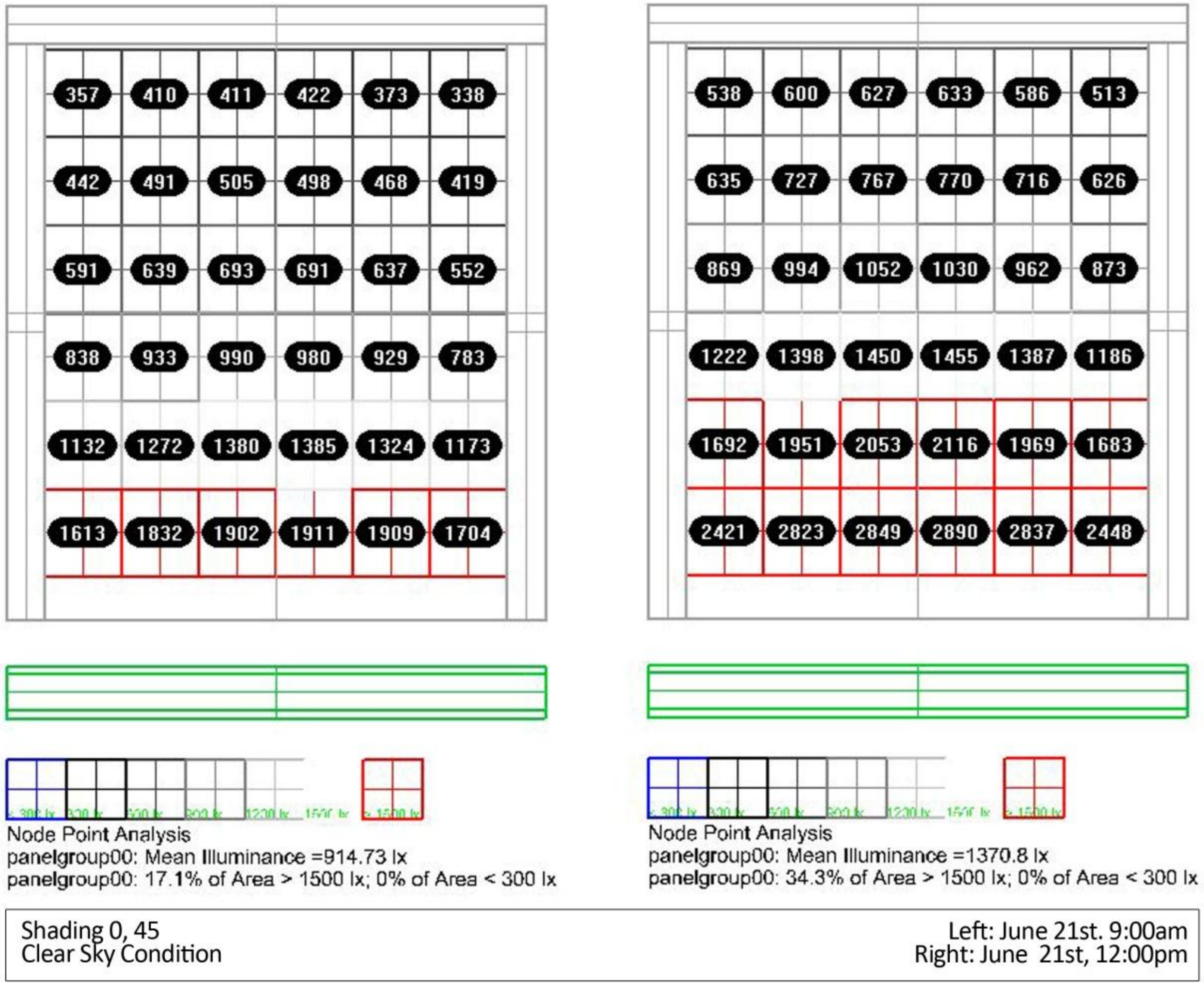


Figure 9-20: Shading 0° and 45° results - The figure shows the illuminance node values inside the space.

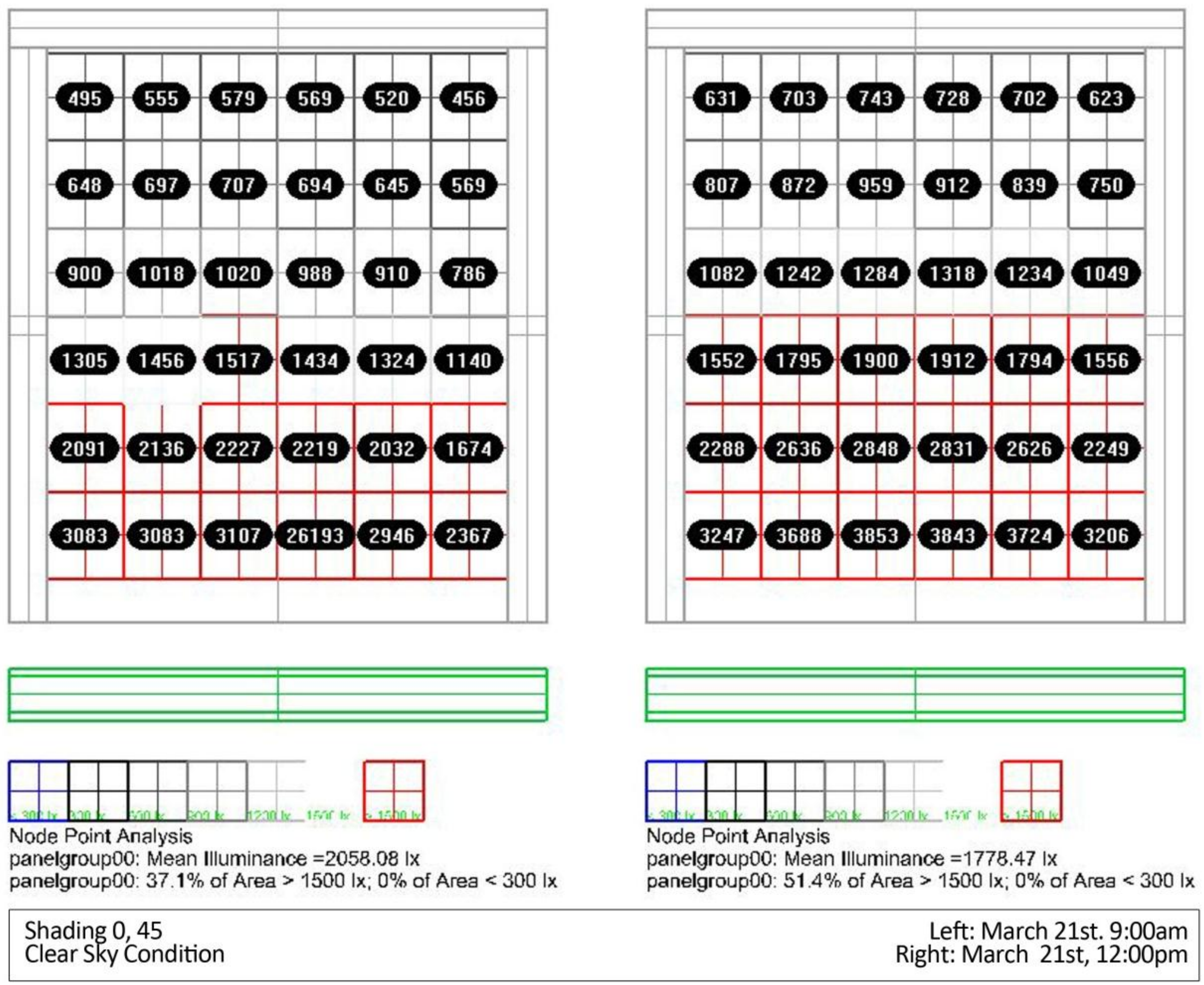


Figure 9-21: Shading 0° and 45° results - The figure shows the illuminance node values inside the space.

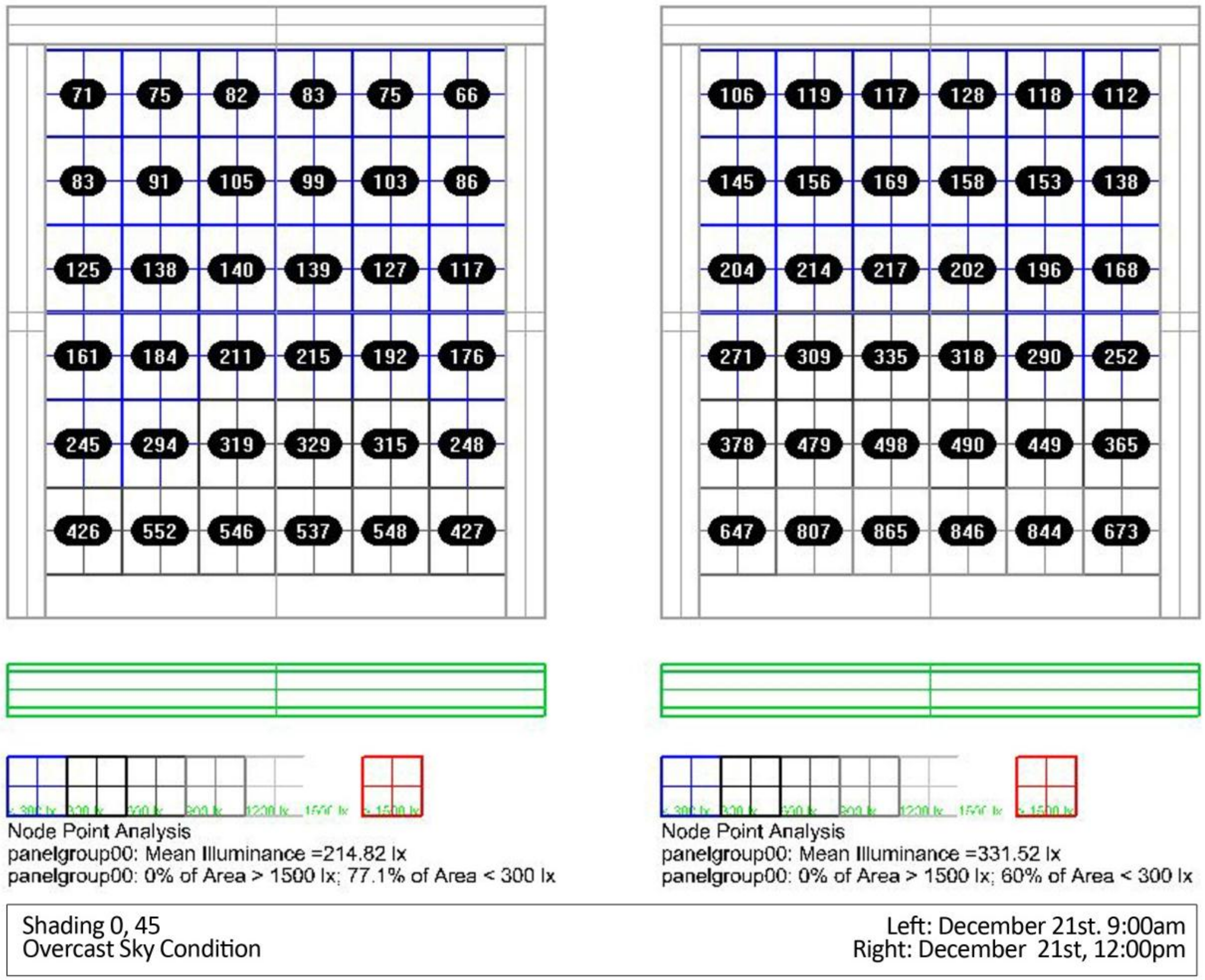


Figure 9-22: Shading 0° and 45° results - The figure shows the illuminance node values inside the space.

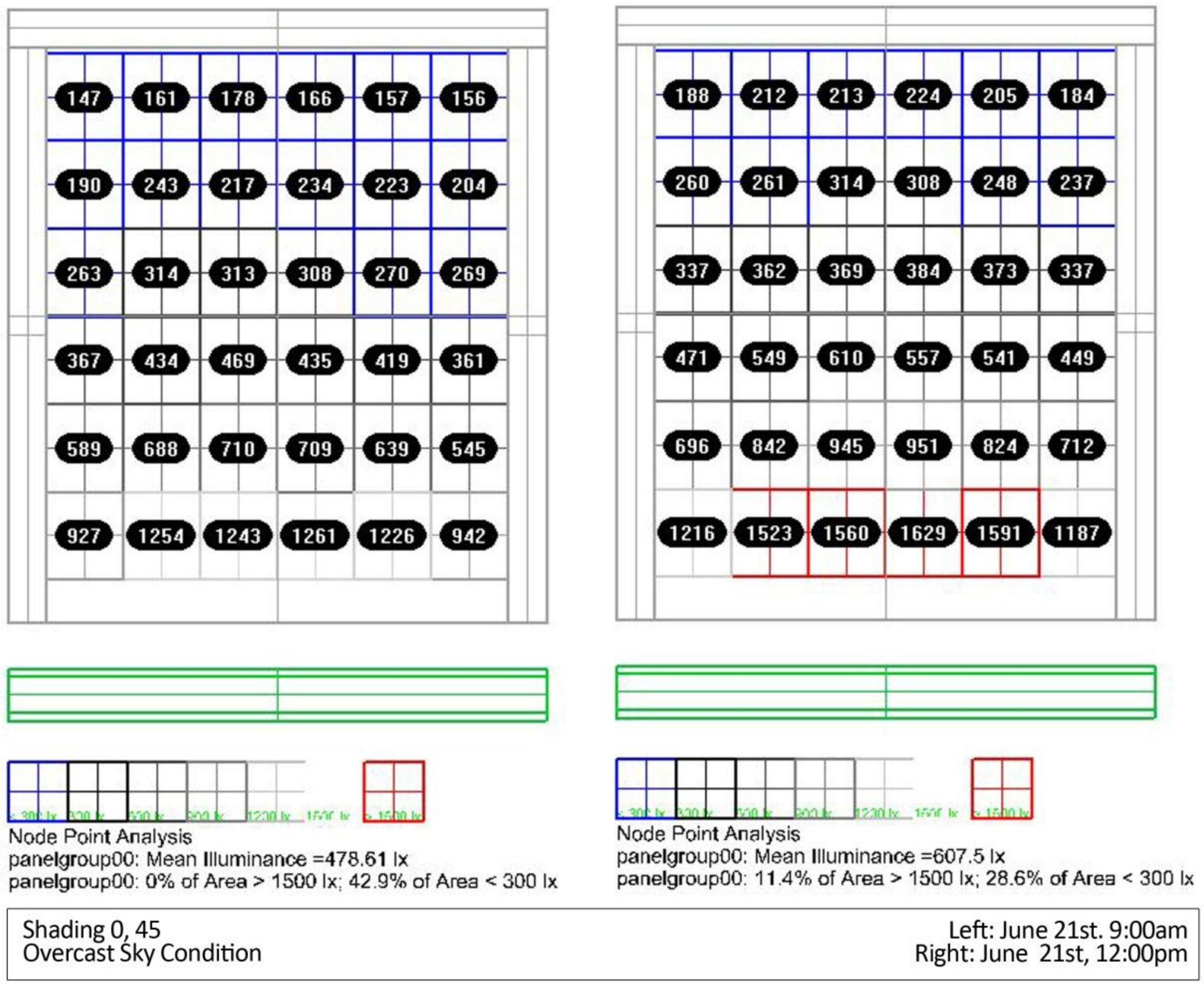
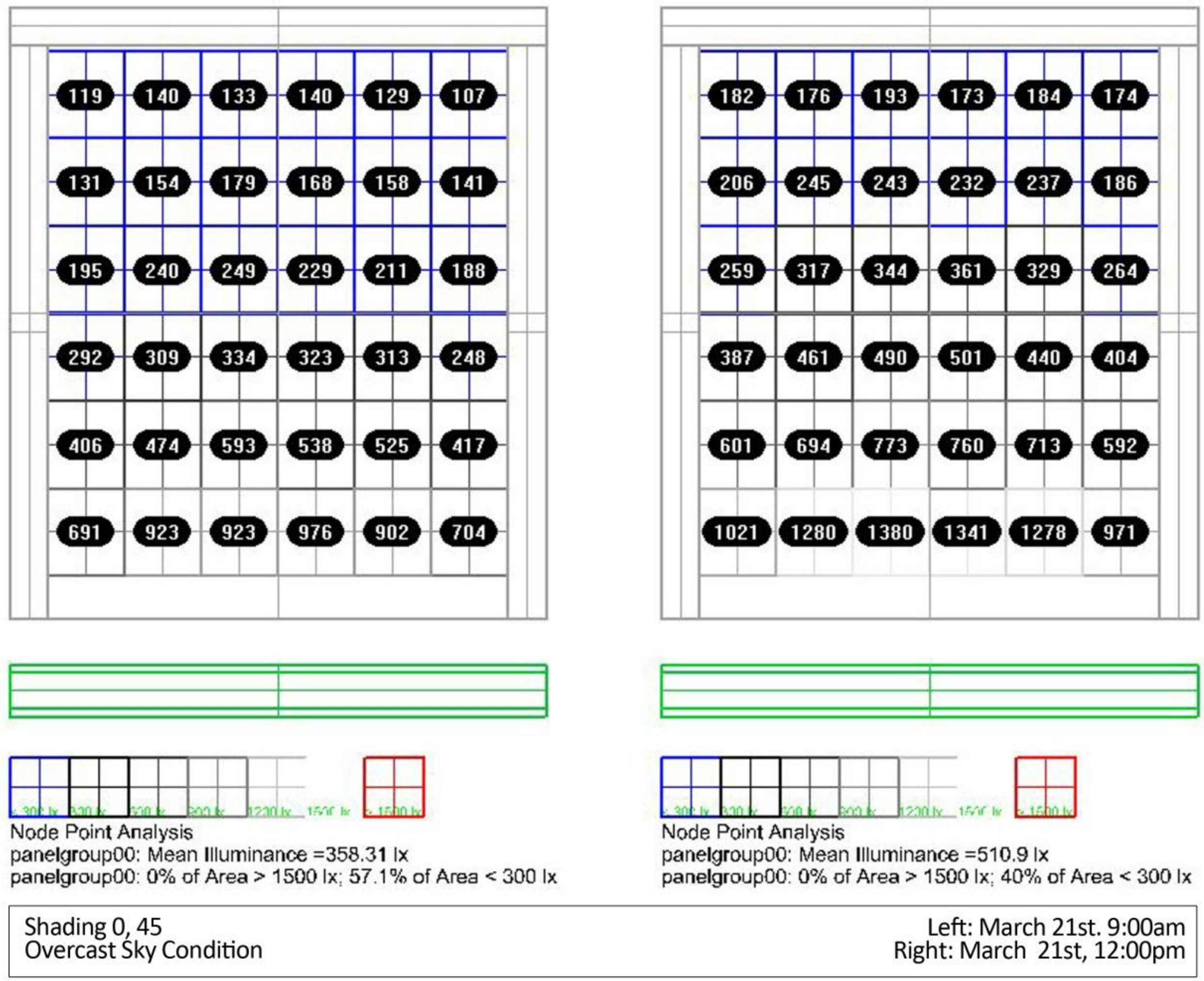


Figure 9-23: Shading 0° and 45° results - The figure shows the illuminance node values inside the space.



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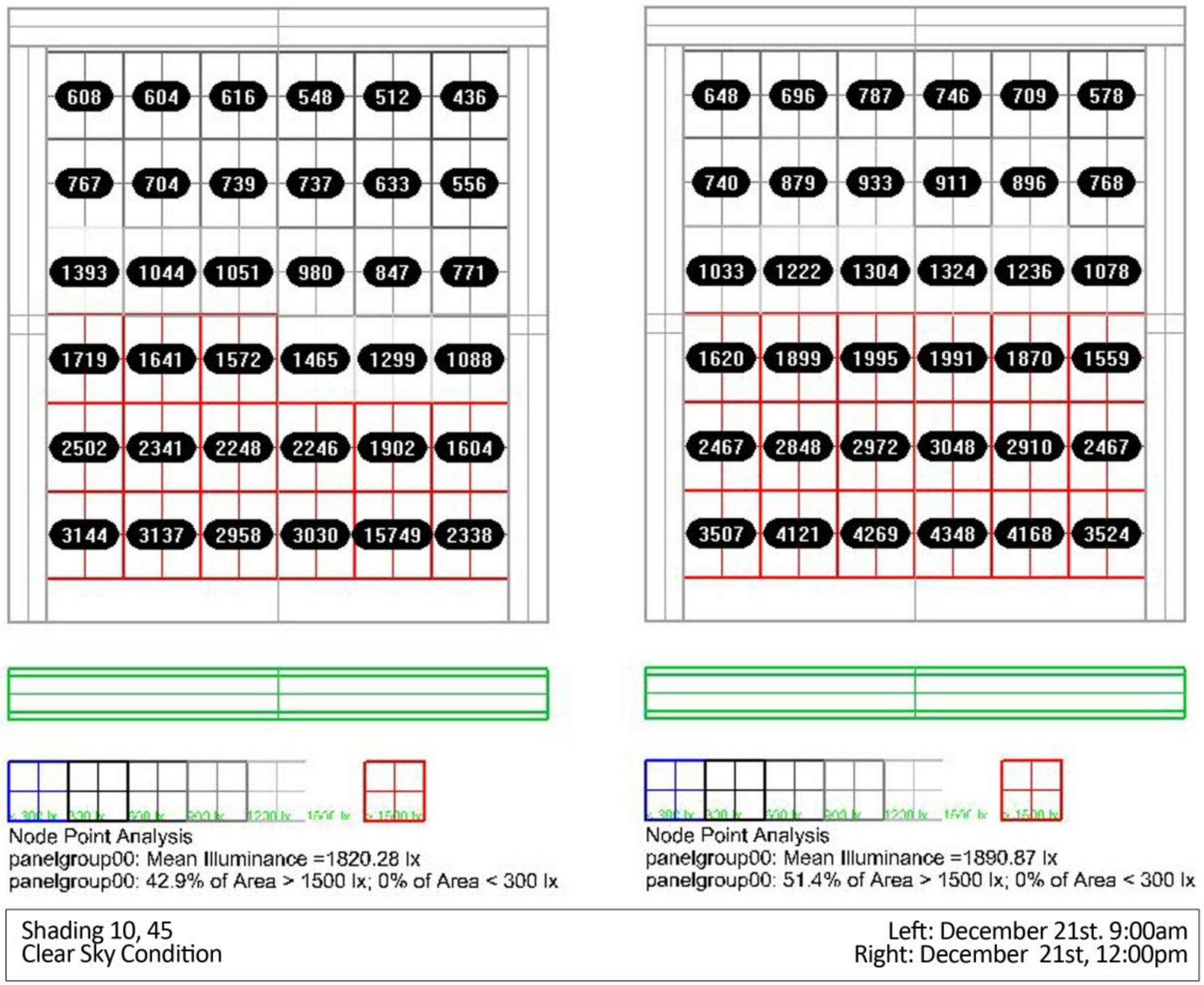

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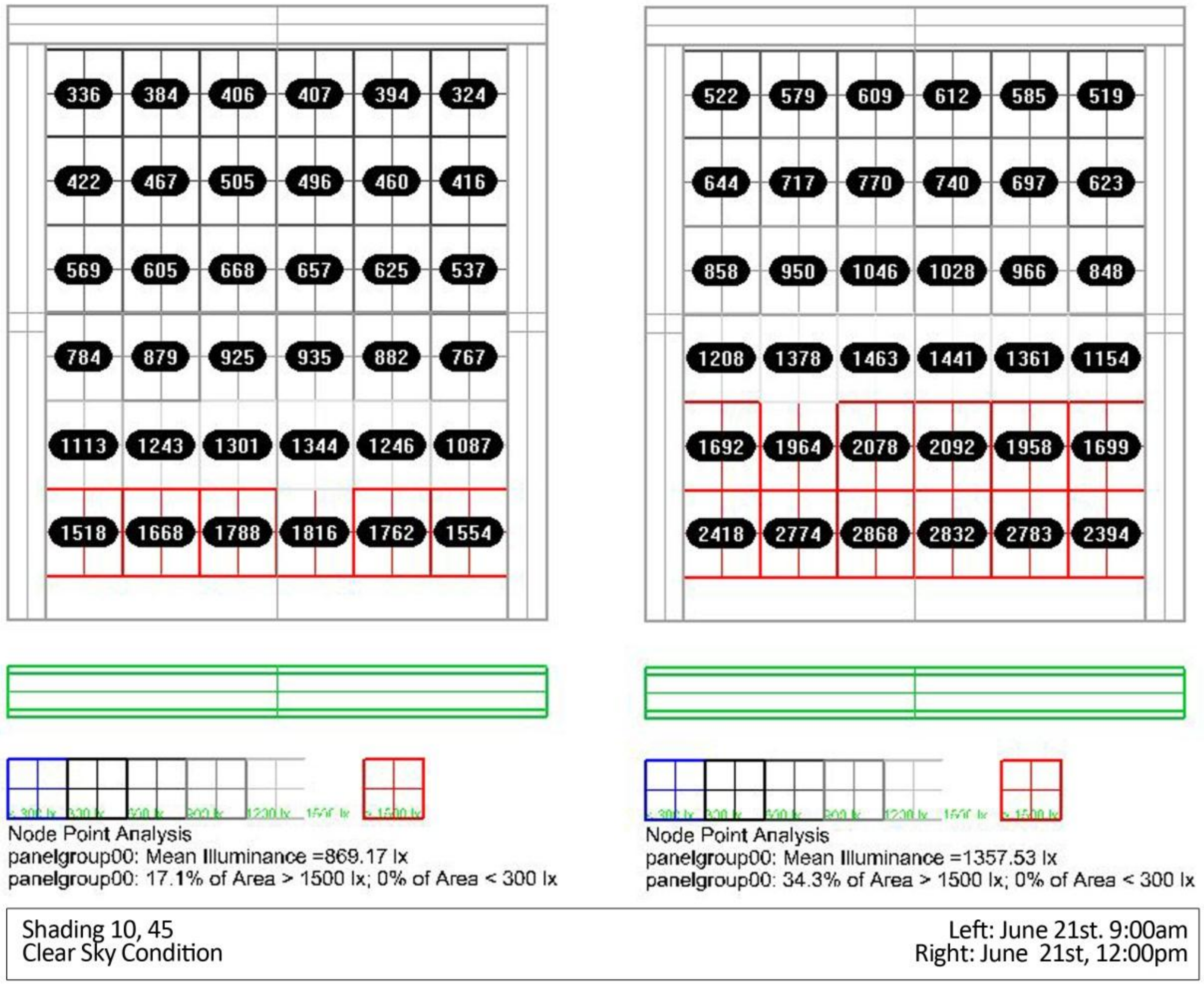


Figure 9-26: Shading 10° and 45° results - The figure shows the illuminance node values inside the space.

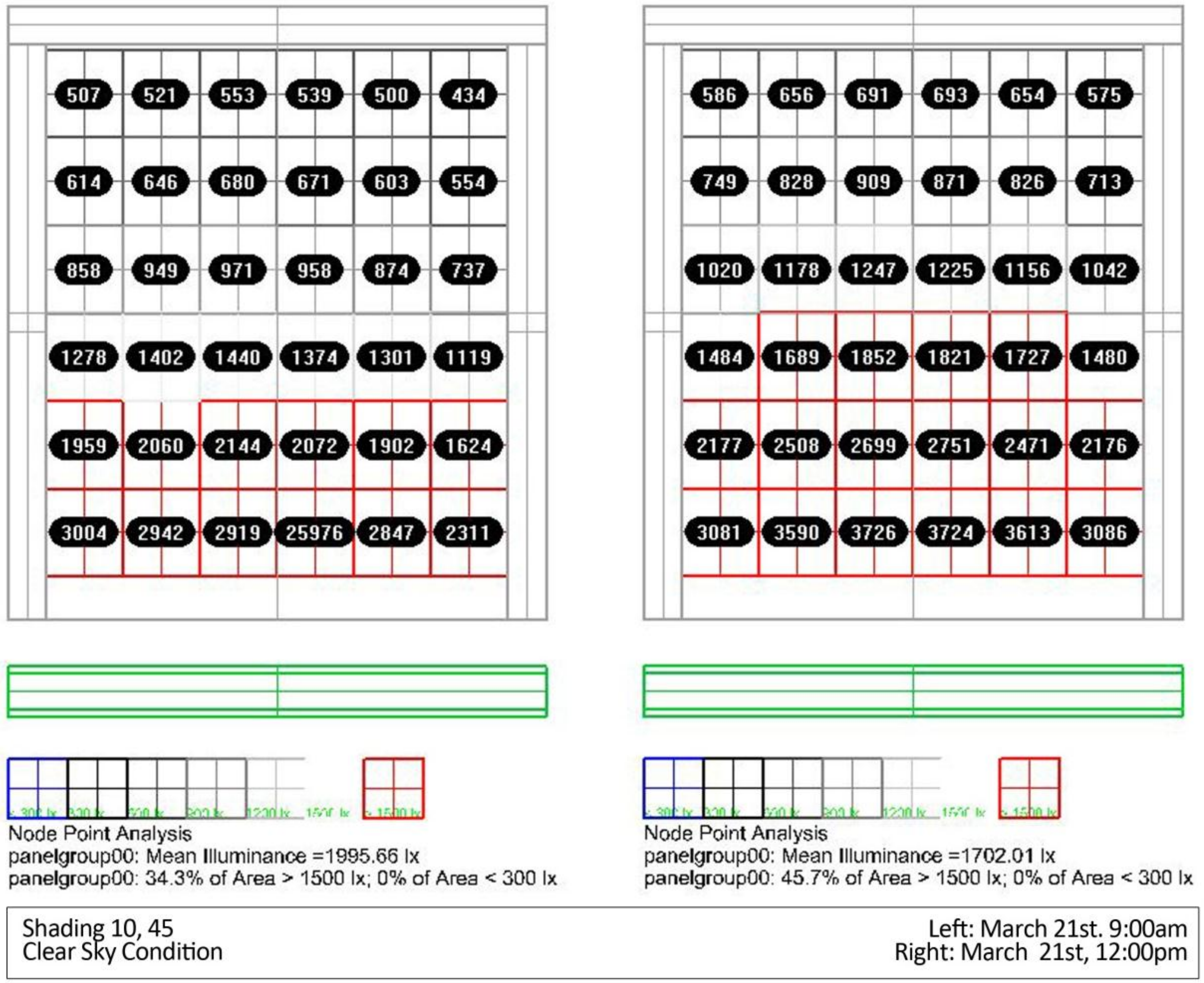
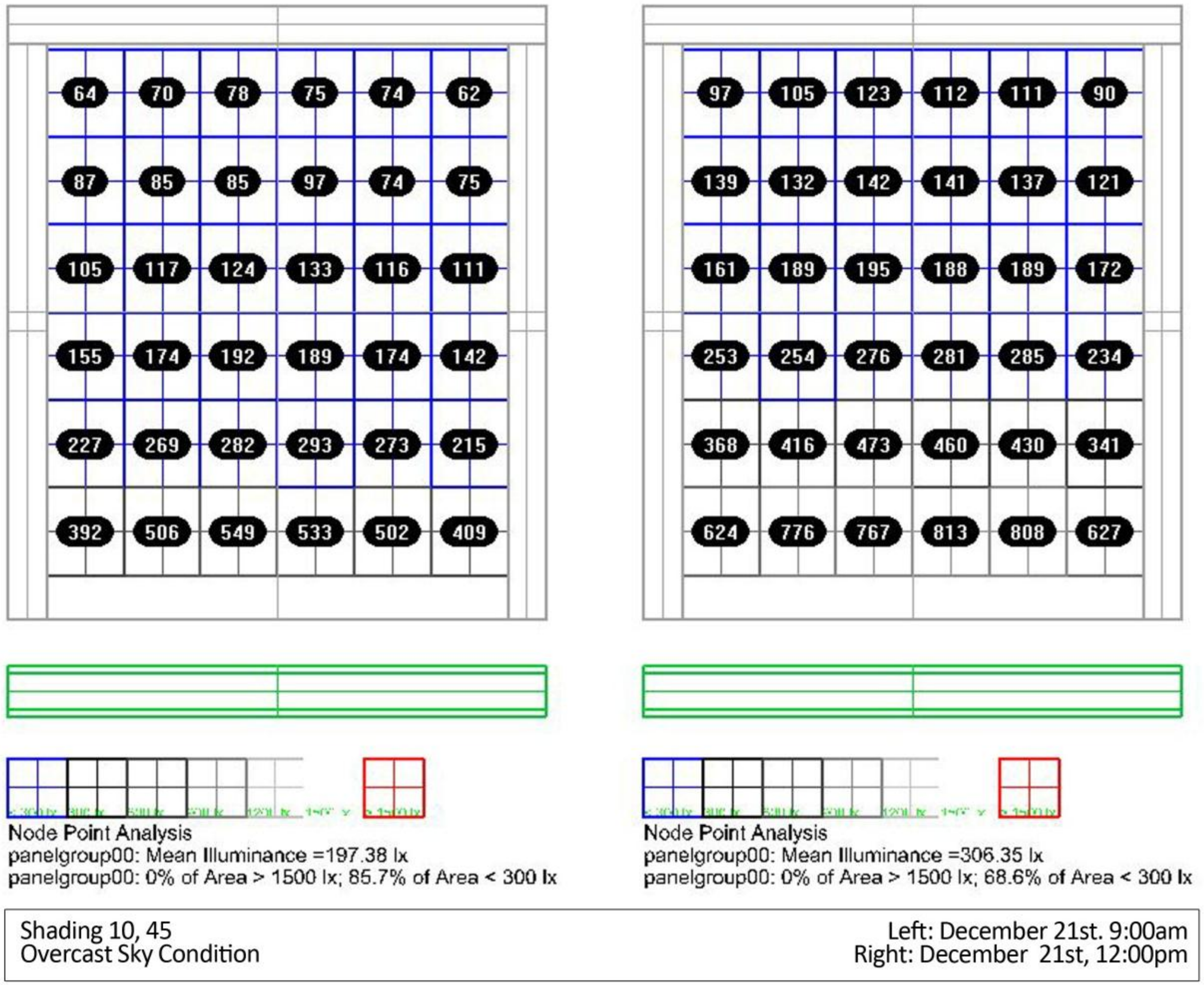


Figure 9-27: Shading 10° and 45° results - The figure shows the illuminance node values inside the space.



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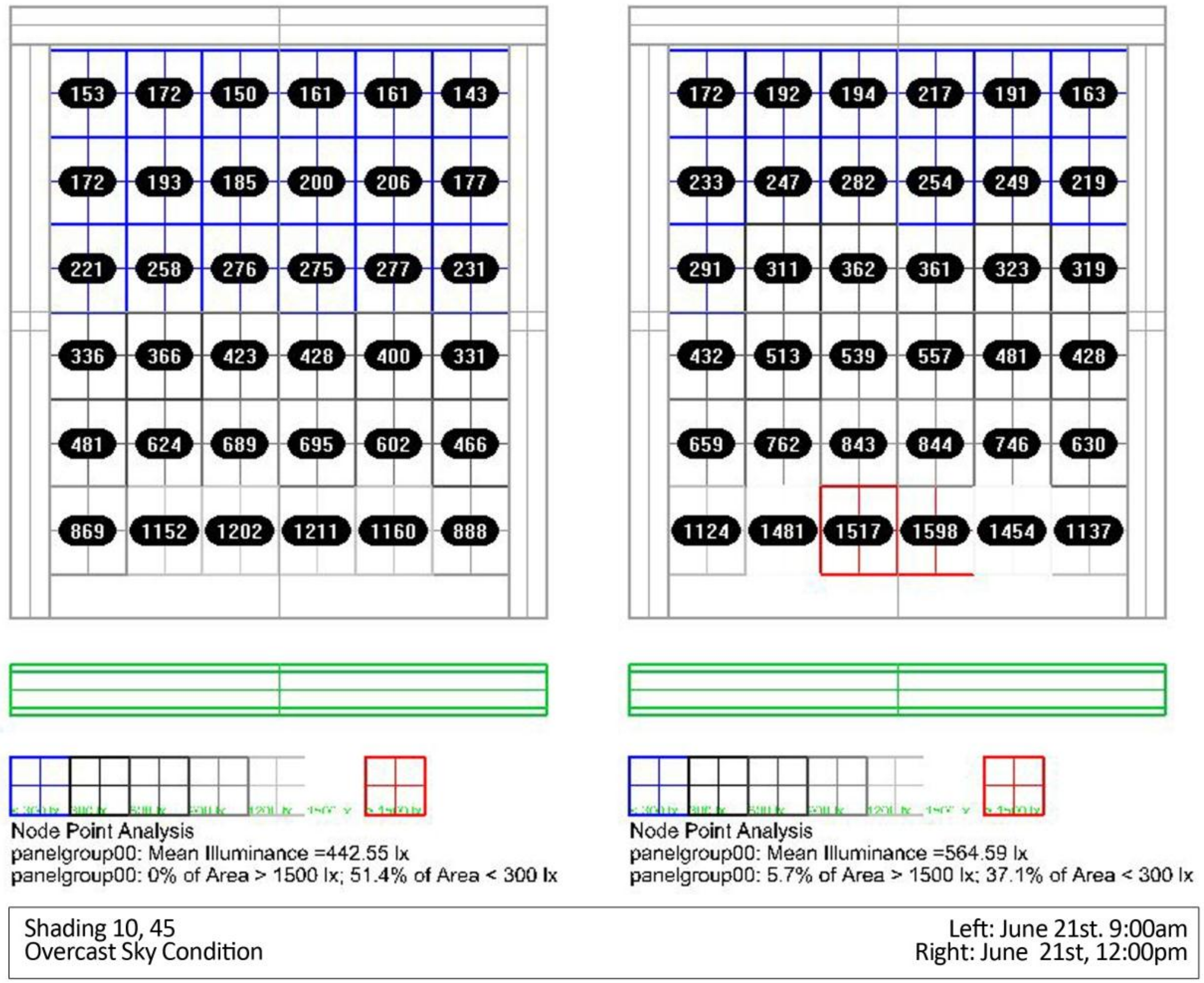

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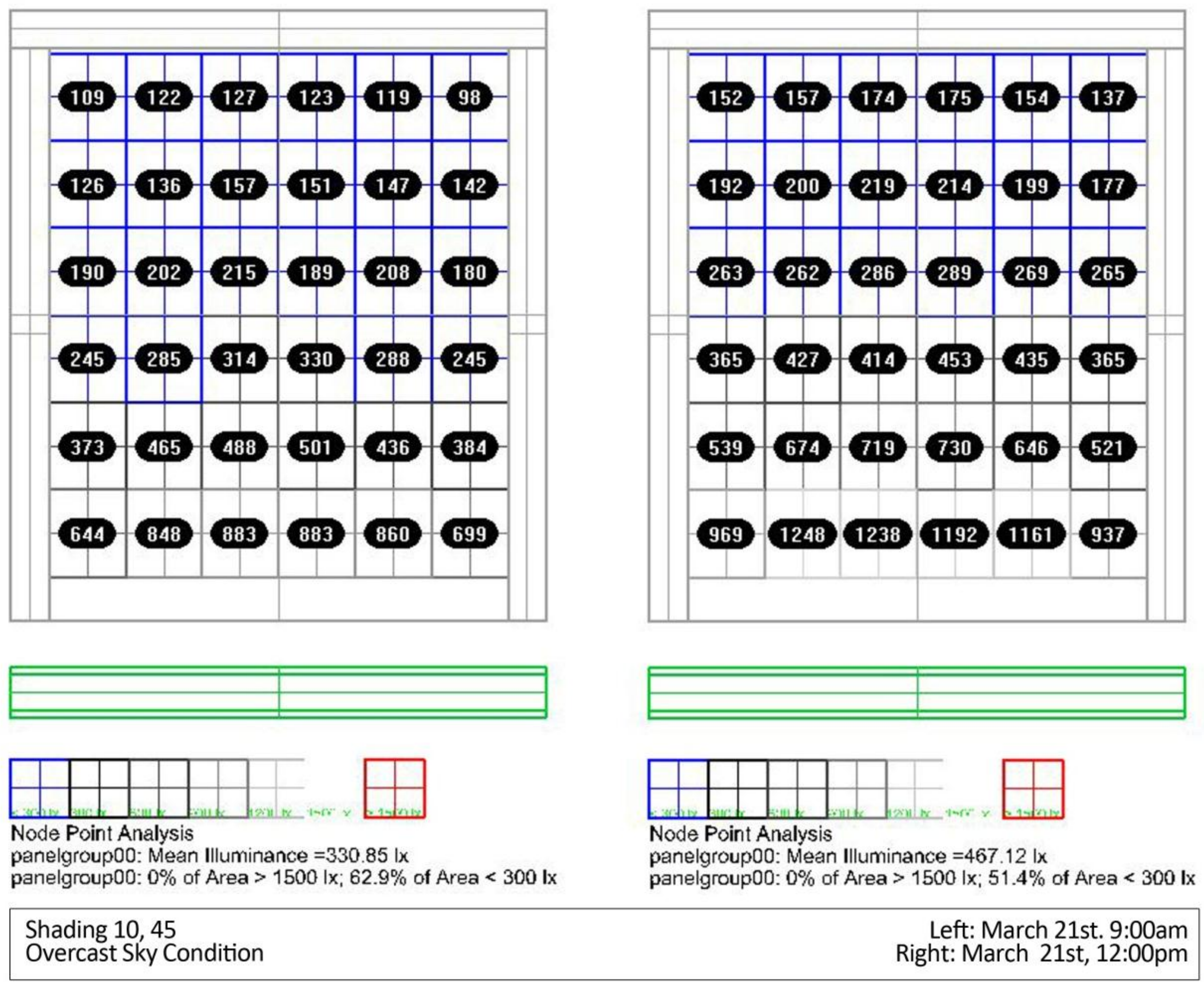

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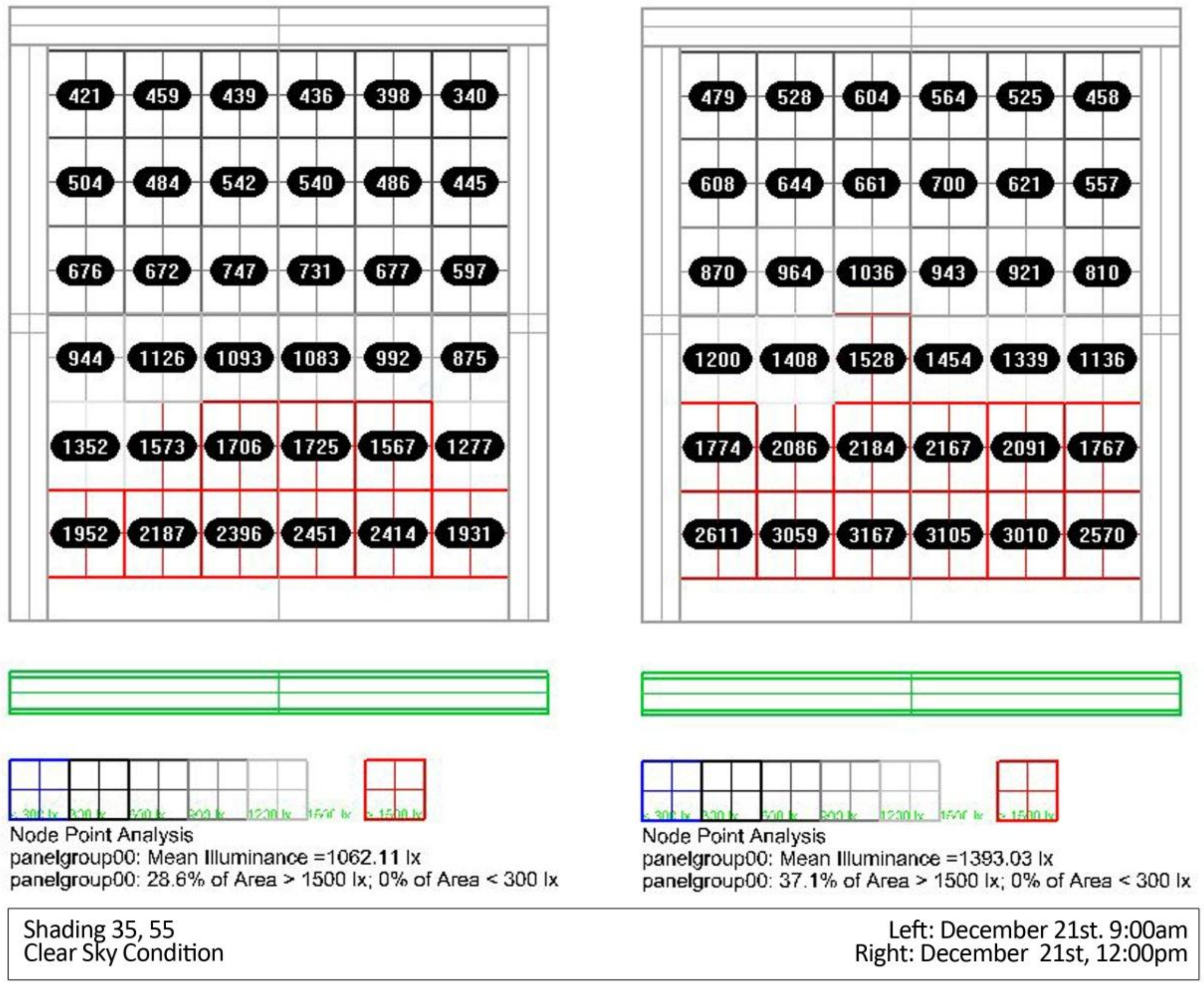
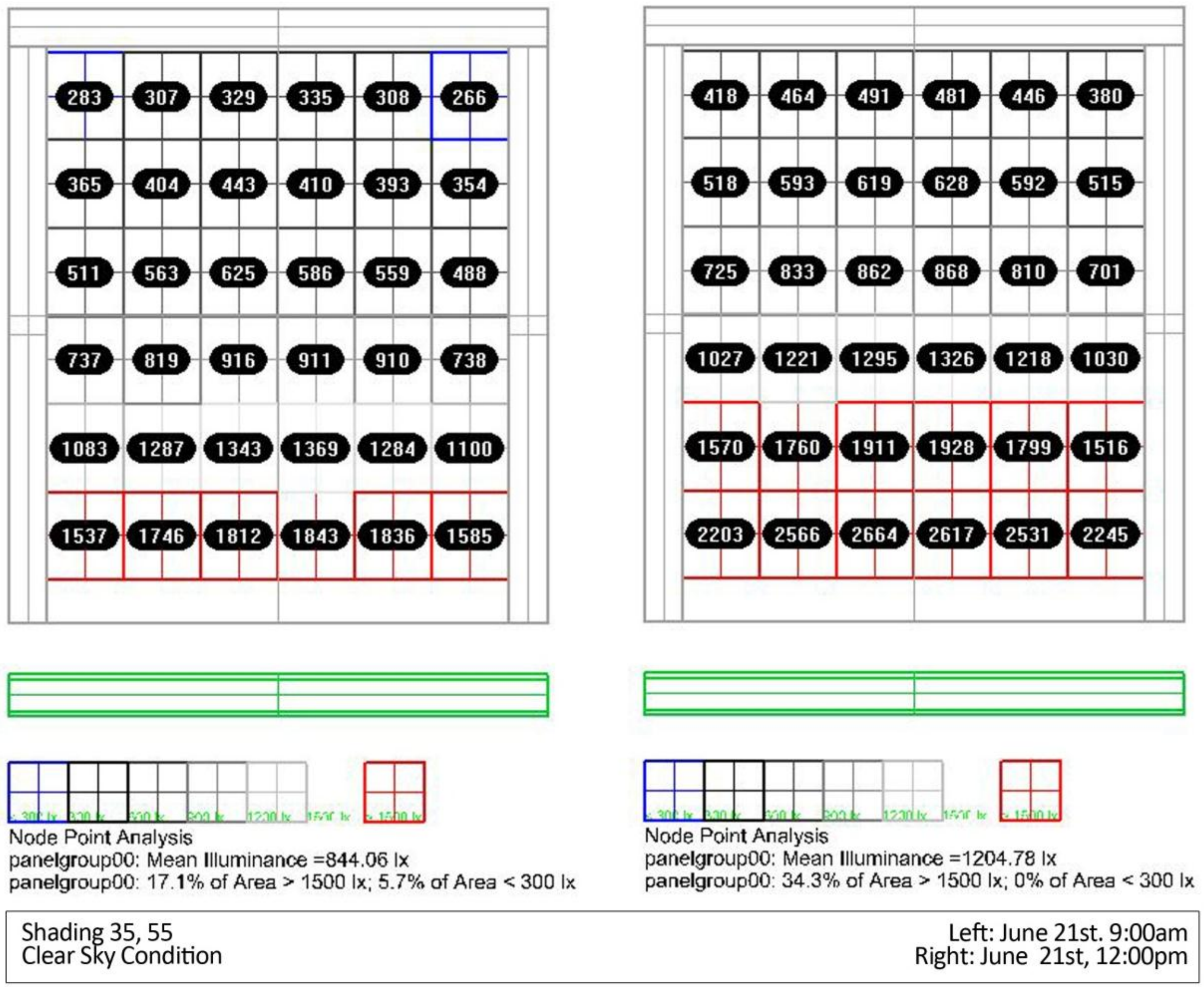


Figure 9-31: Shading 35° and 55° results - The figure shows the illuminance node values inside the space.



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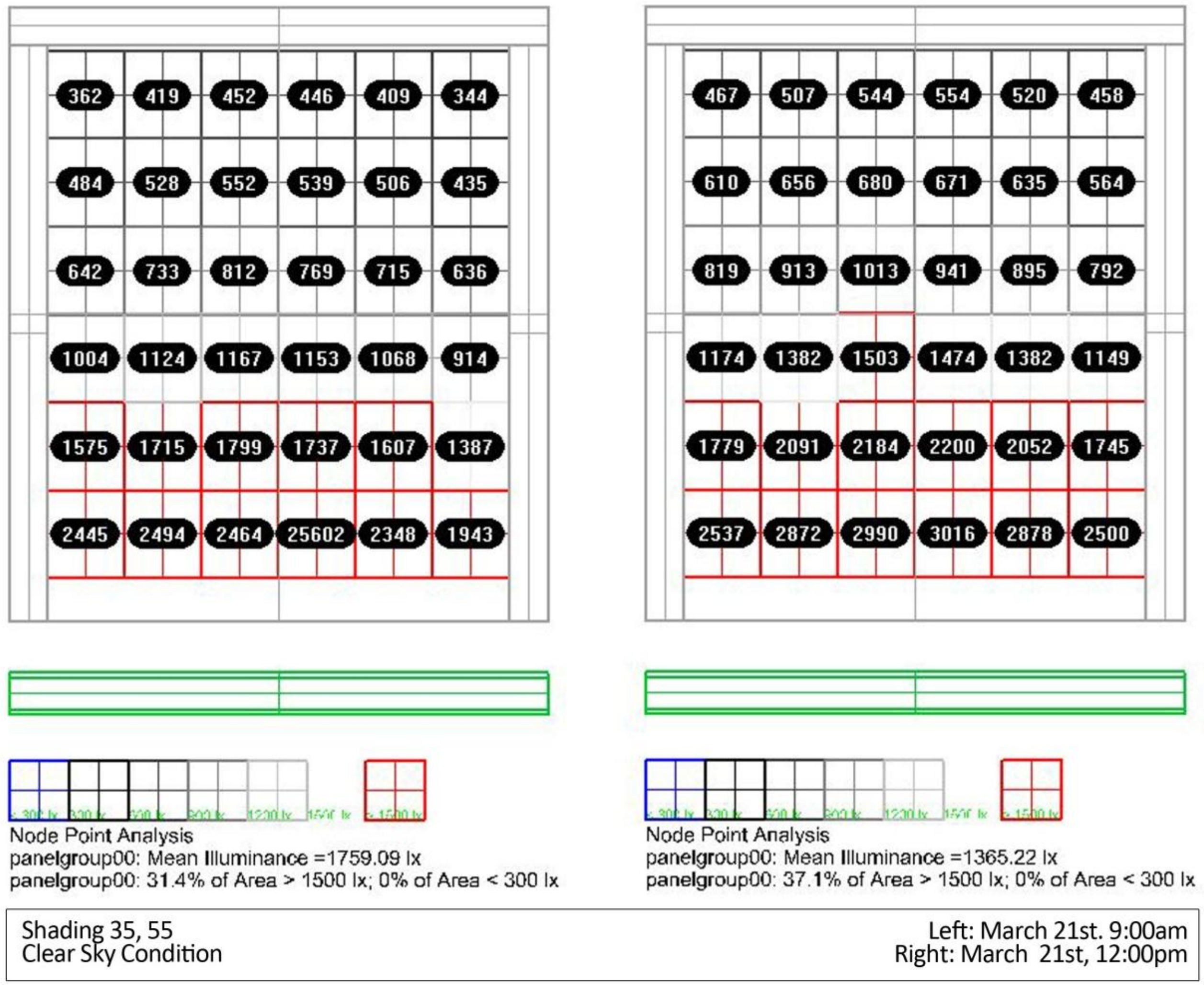

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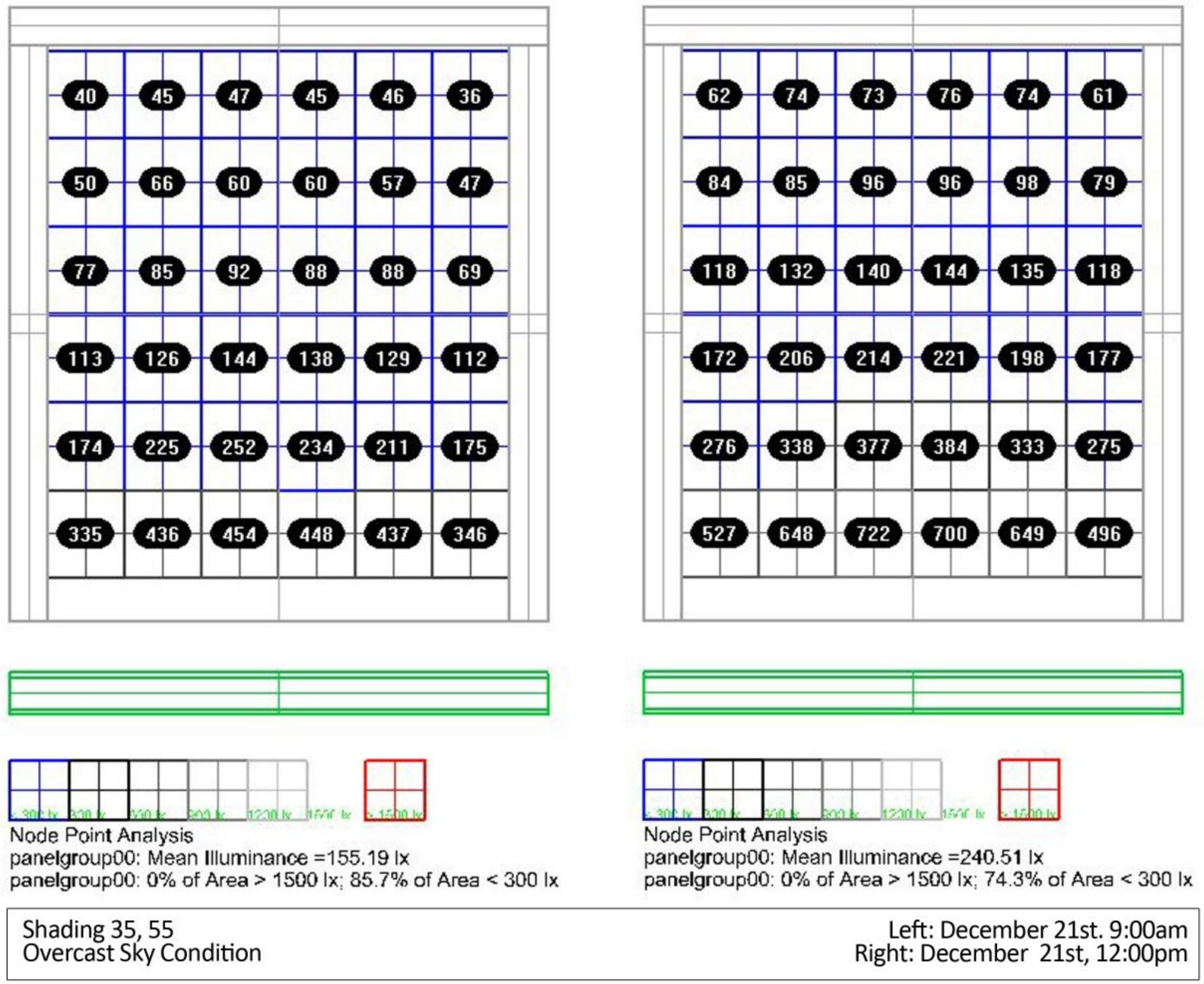

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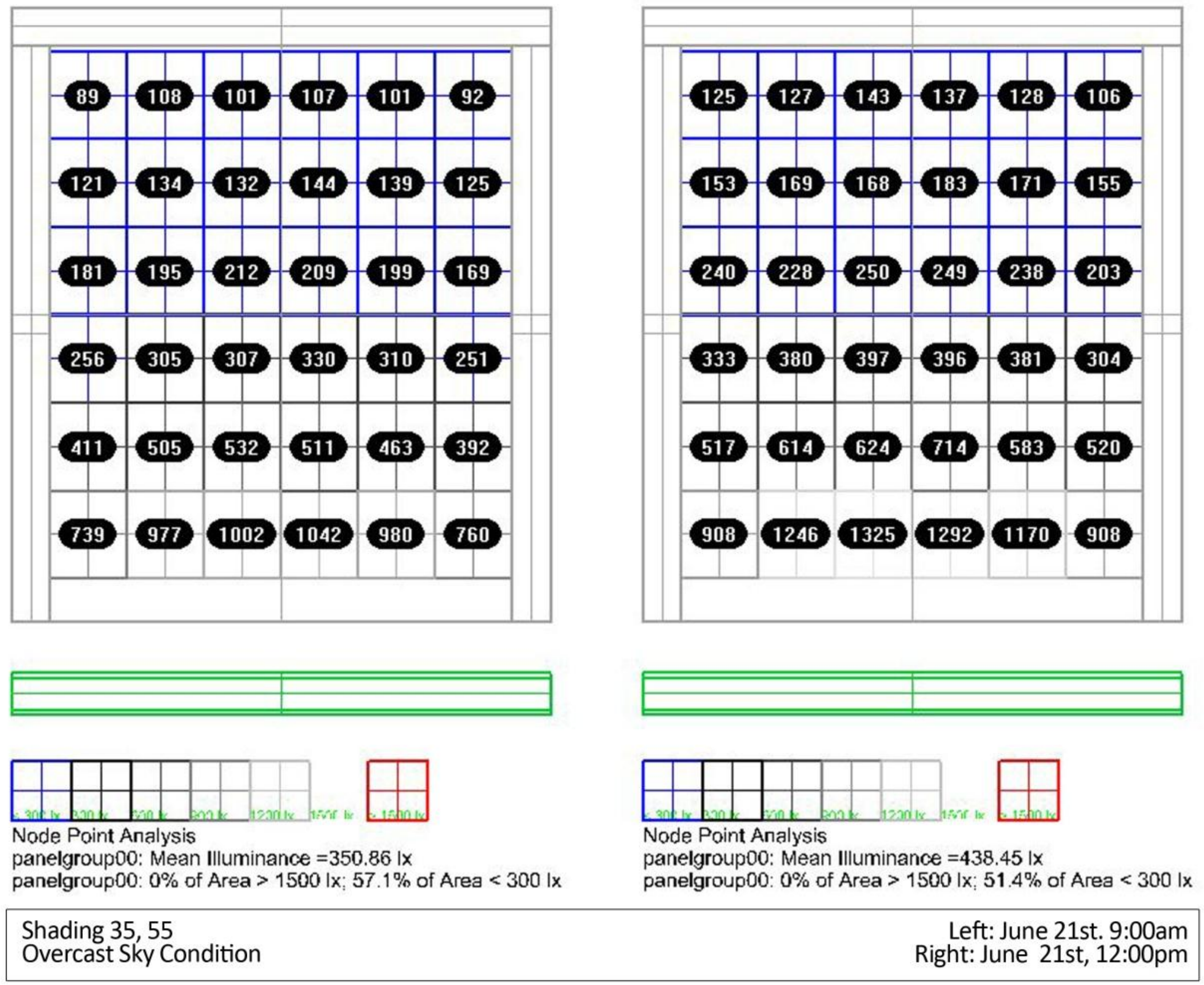

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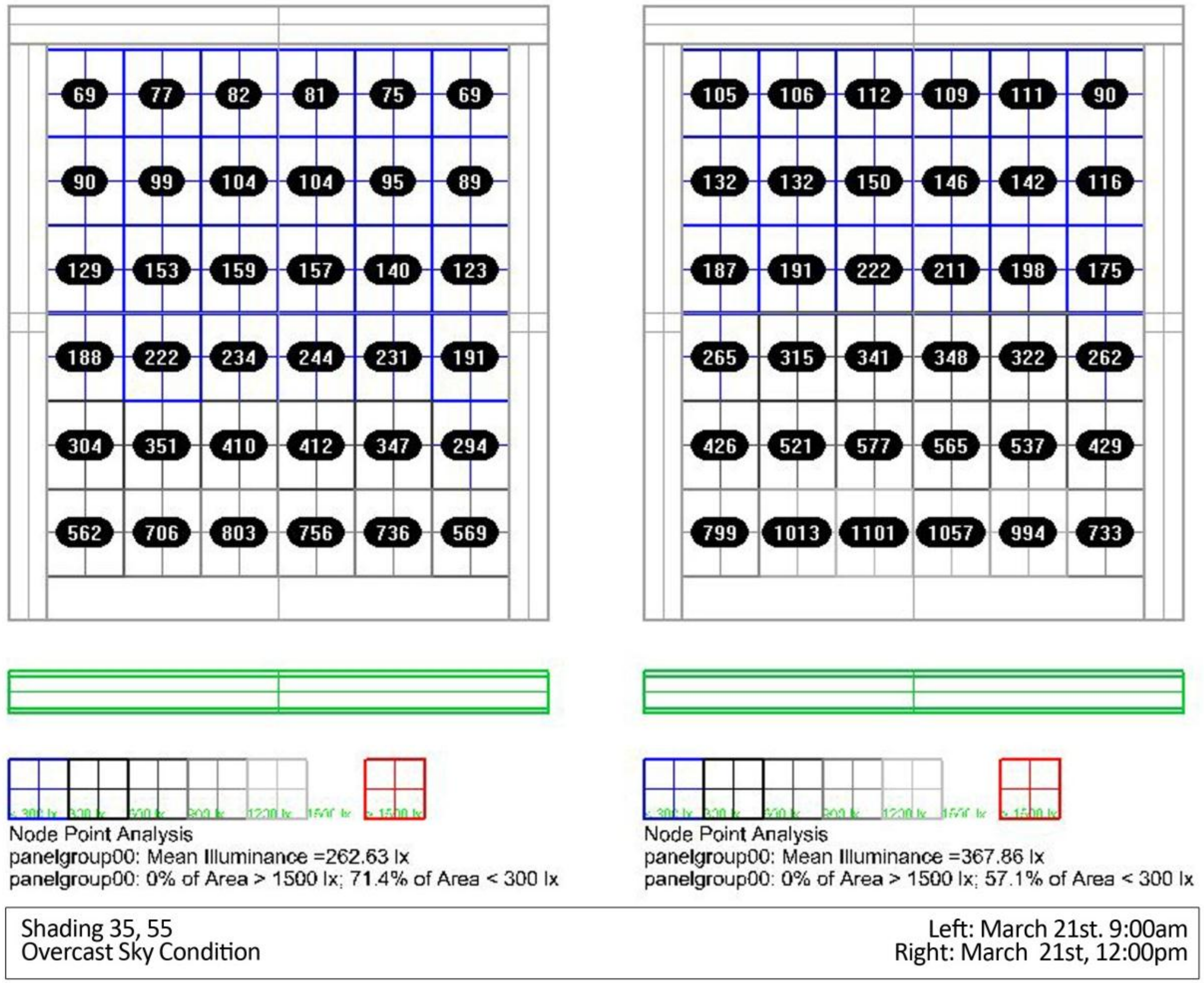


Figure 9-36: Shading 35° and 55° results - The figure shows the illuminance node values inside the space.

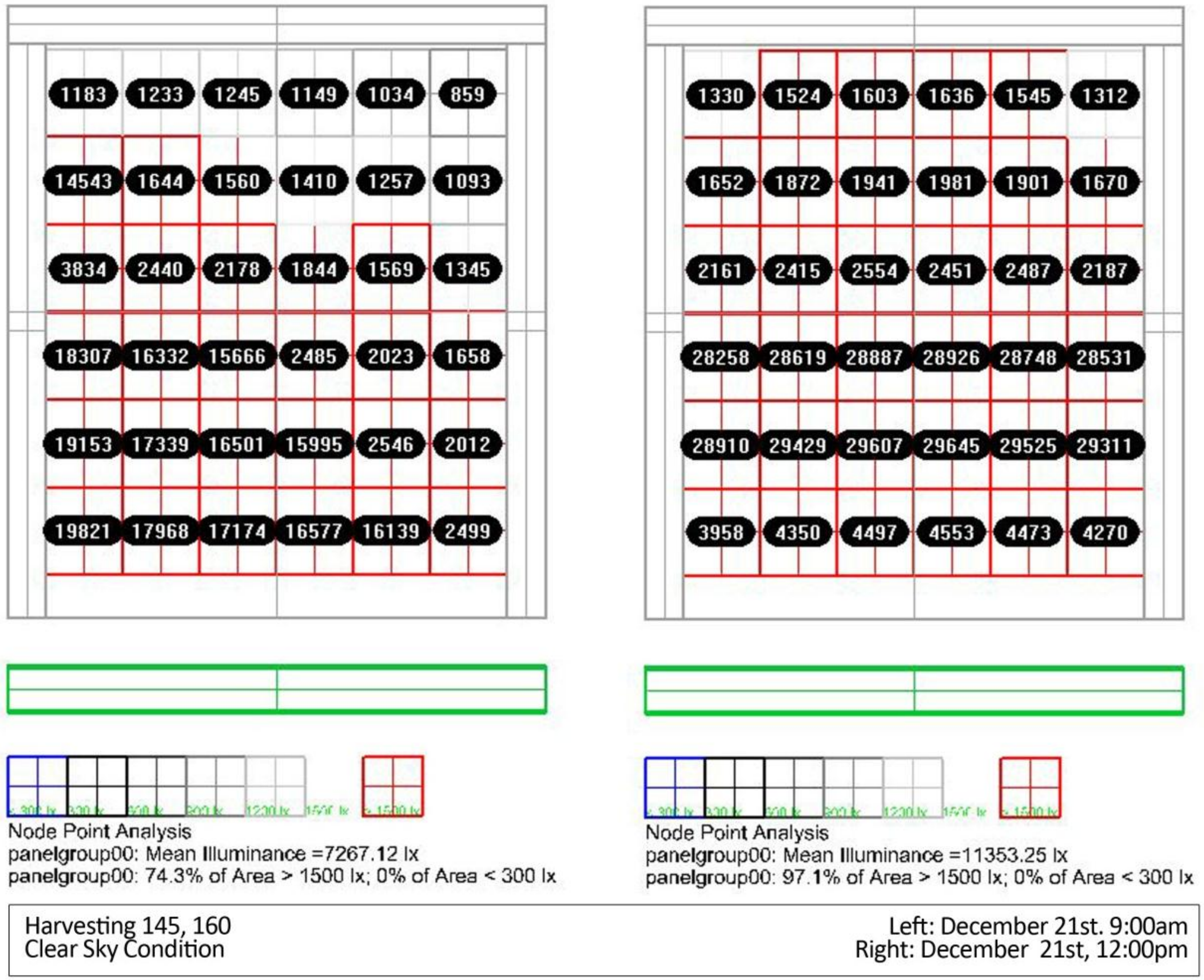


Figure 9-37: Harvesting 145° and 160° results - The figure shows the illuminance node values inside the space.

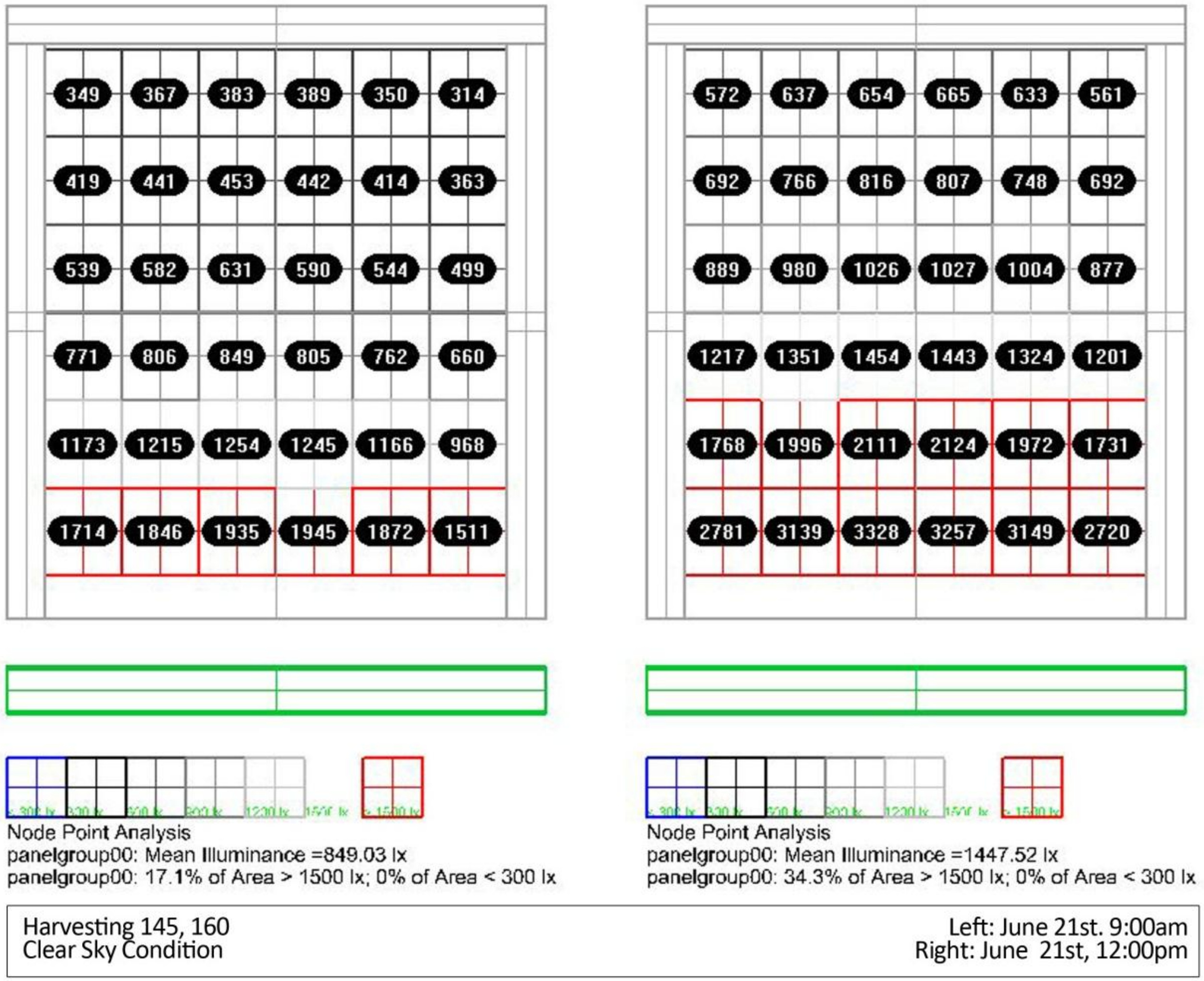


Figure 9-38: Harvesting 145° and 160° results - The figure shows the illuminance node values inside the space.

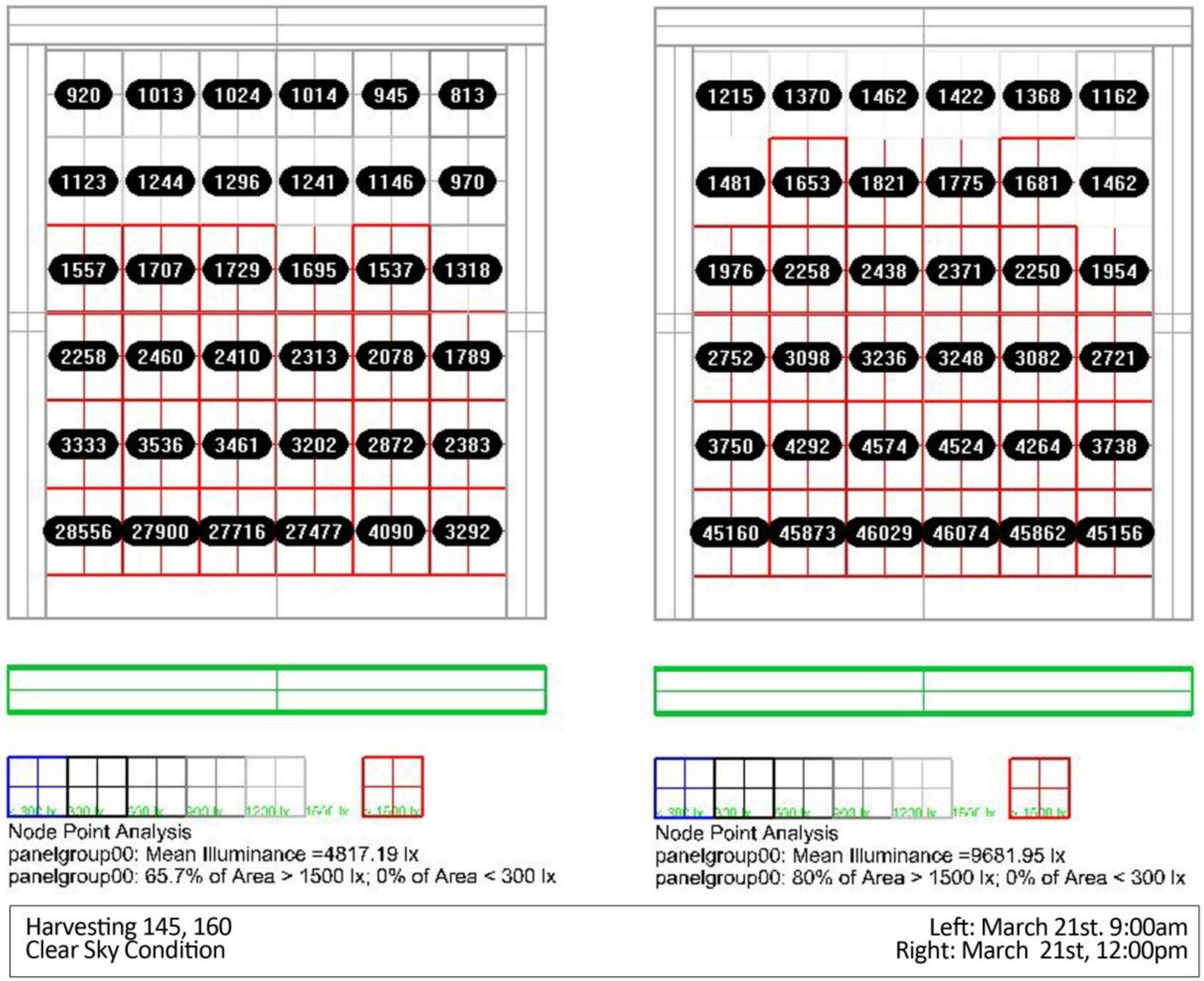


Figure 9-39: Harvesting 145° and 160° results - The figure shows the illuminance node values inside the space.

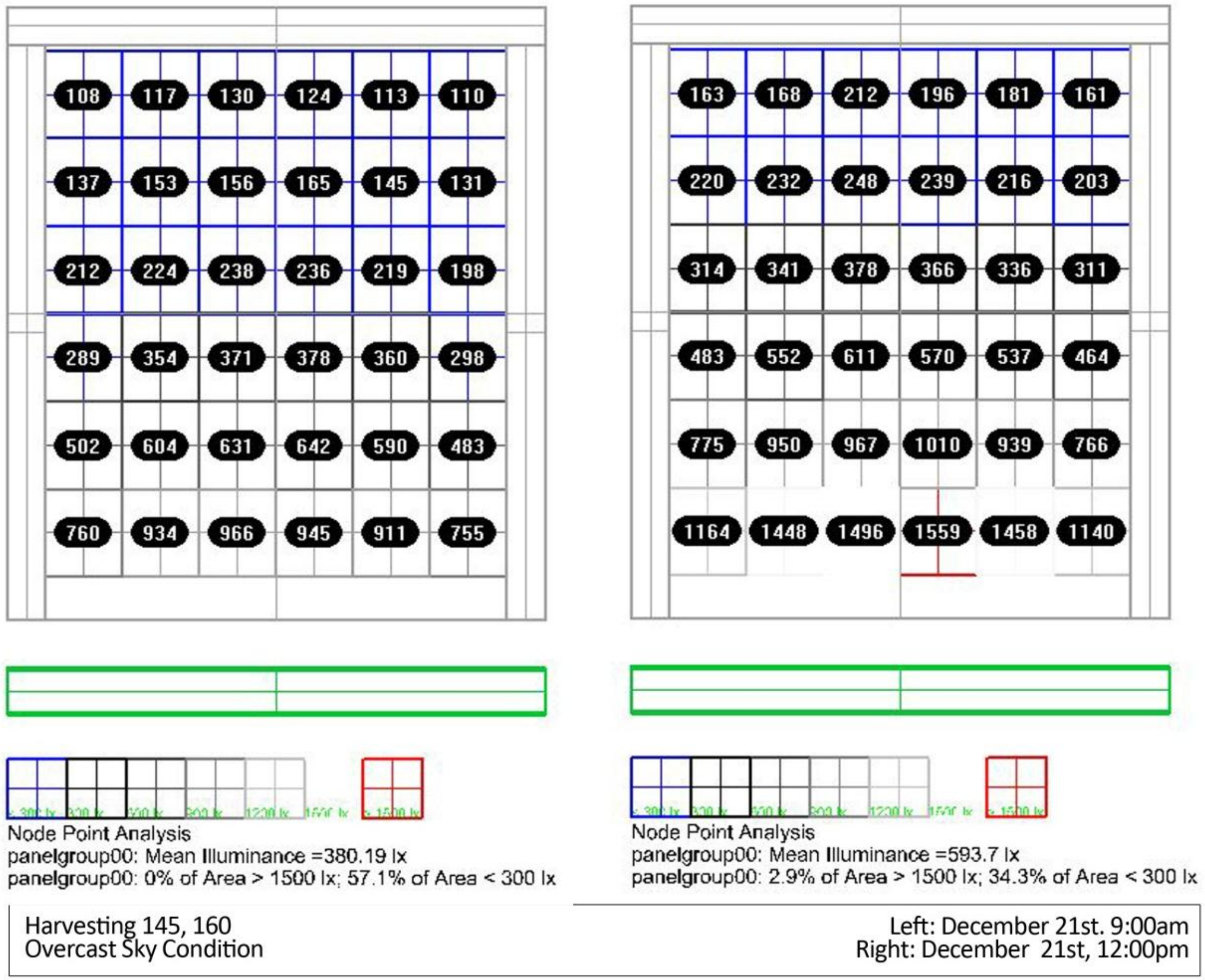


Figure 9-40: Harvesting 145° and 160° results - The figure shows the illuminance node values inside the space.

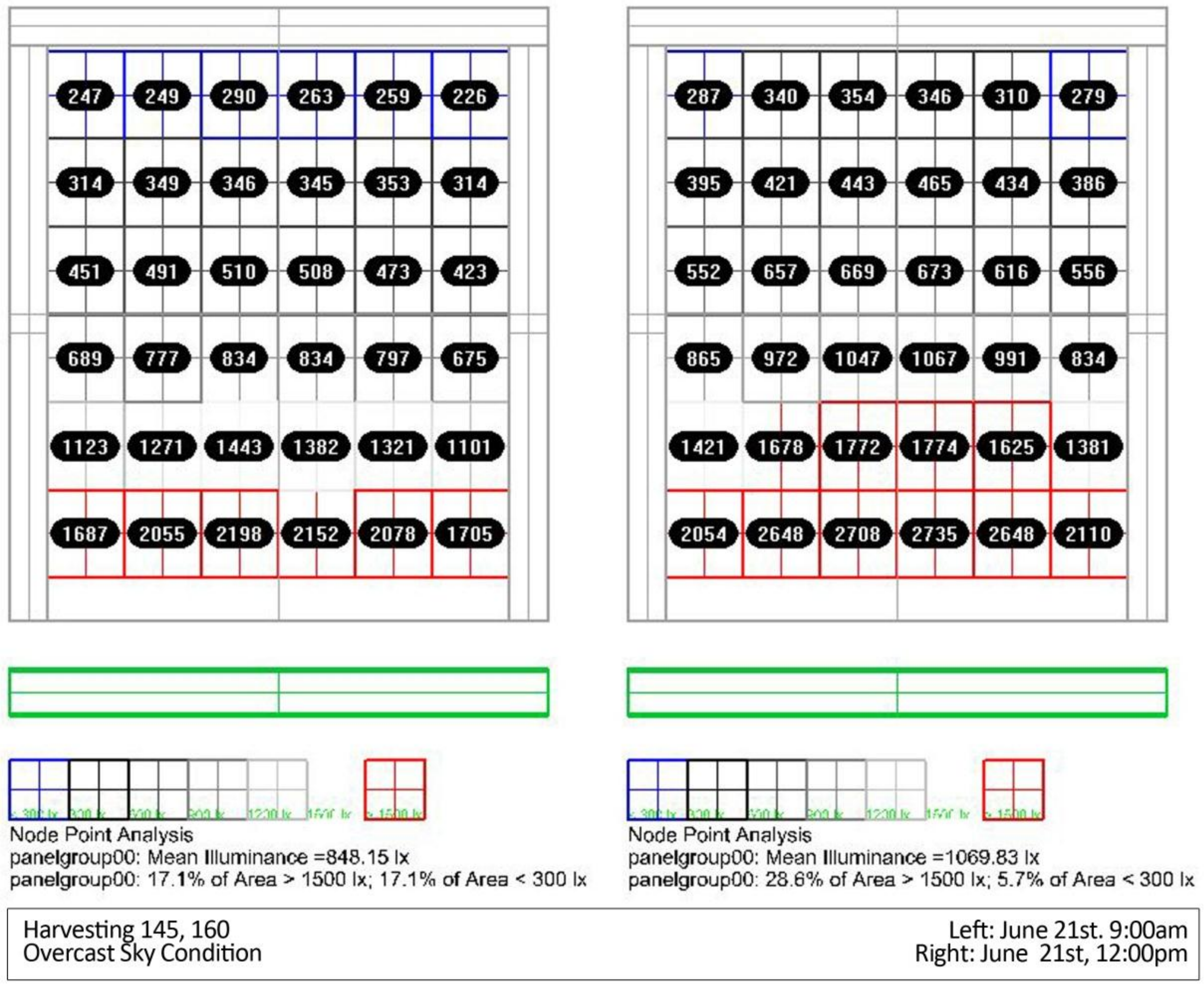


Figure 9-41: Harvesting 145° and 160° results - The figure shows the illuminance node values inside the space.

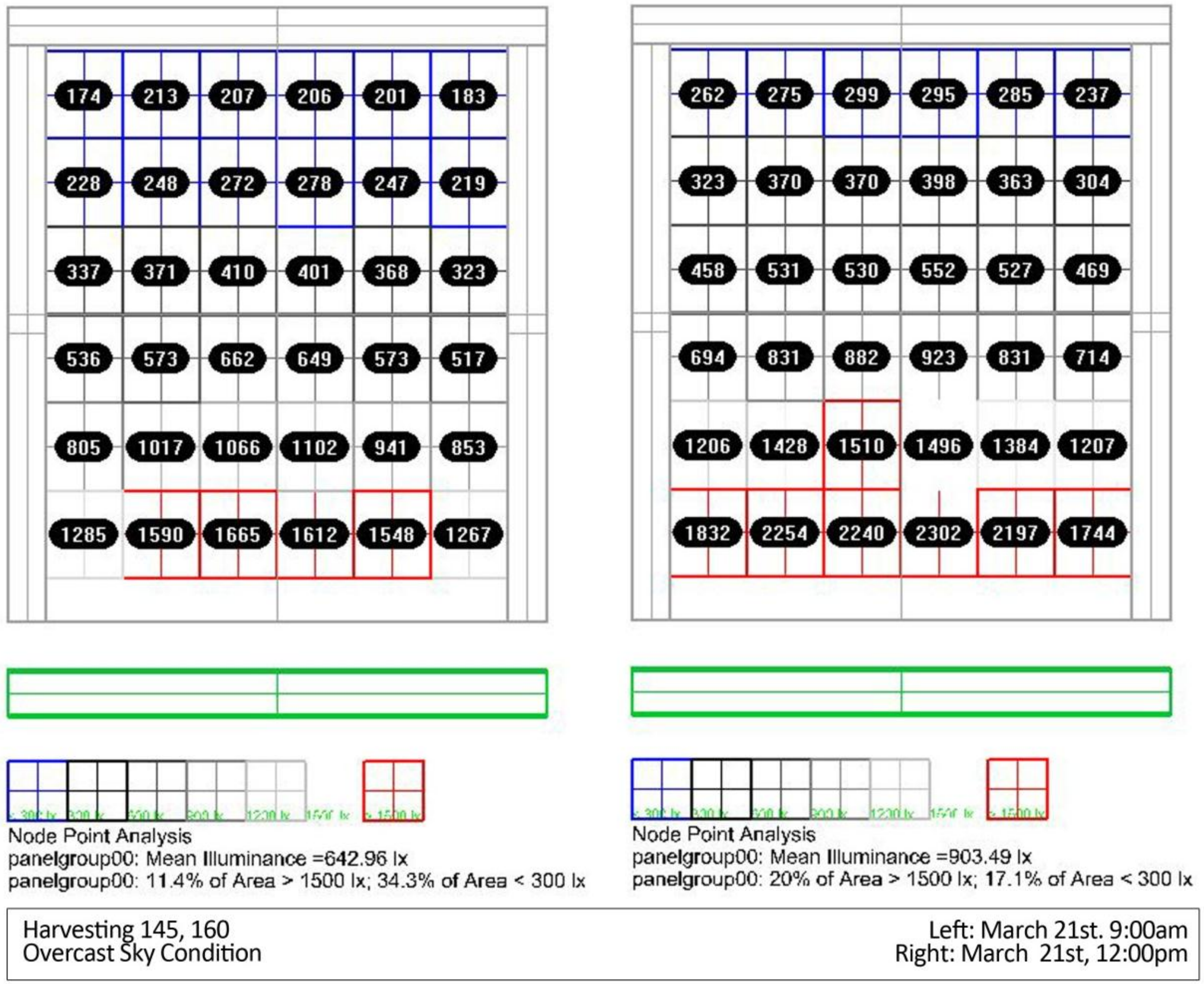


Figure 9-42: Harvesting 145° and 160° results - The figure shows the illuminance node values inside the space.

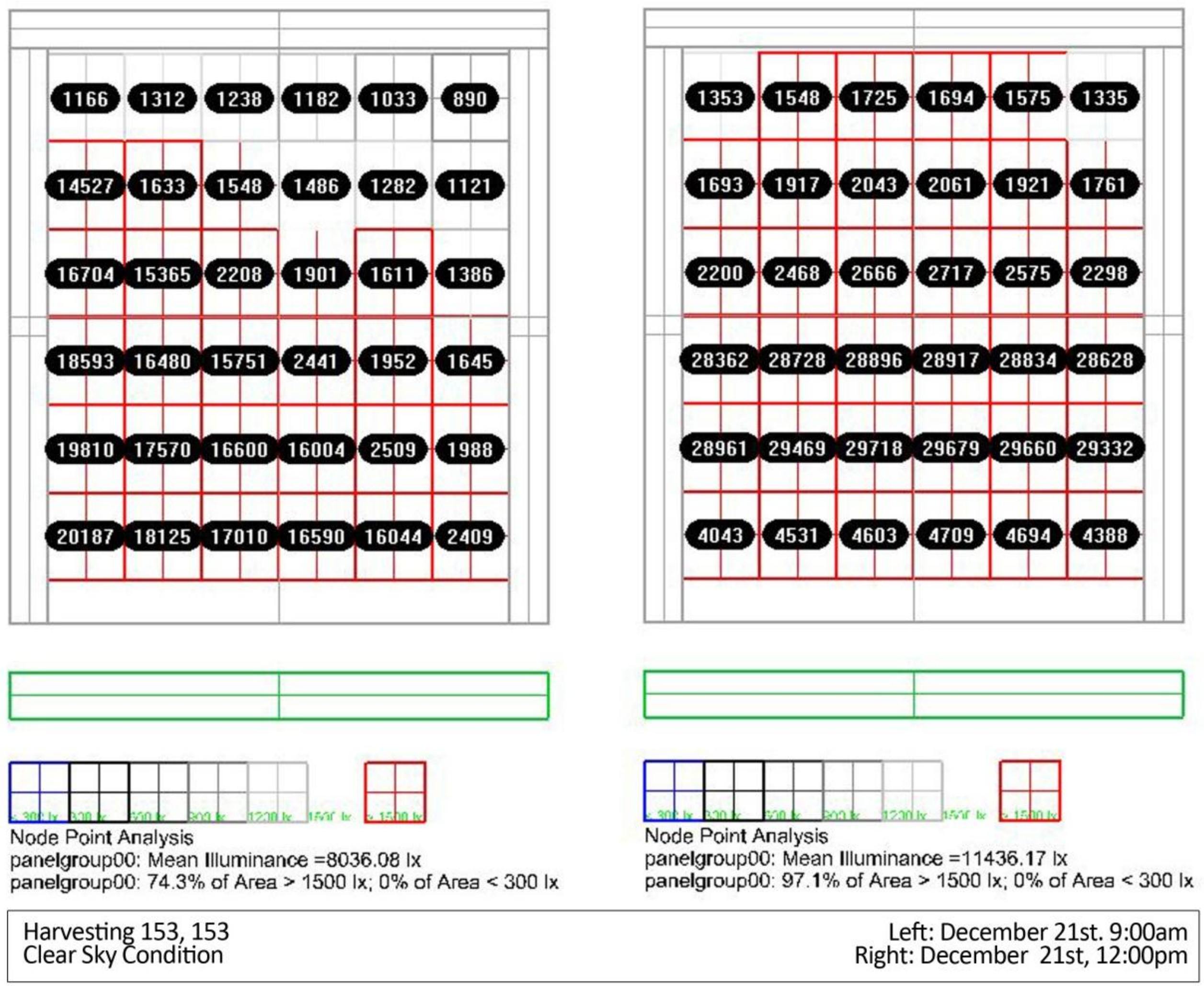


Figure 9-43: Harvesting 153° and 153° results - The figure shows the illuminance node values inside the space.

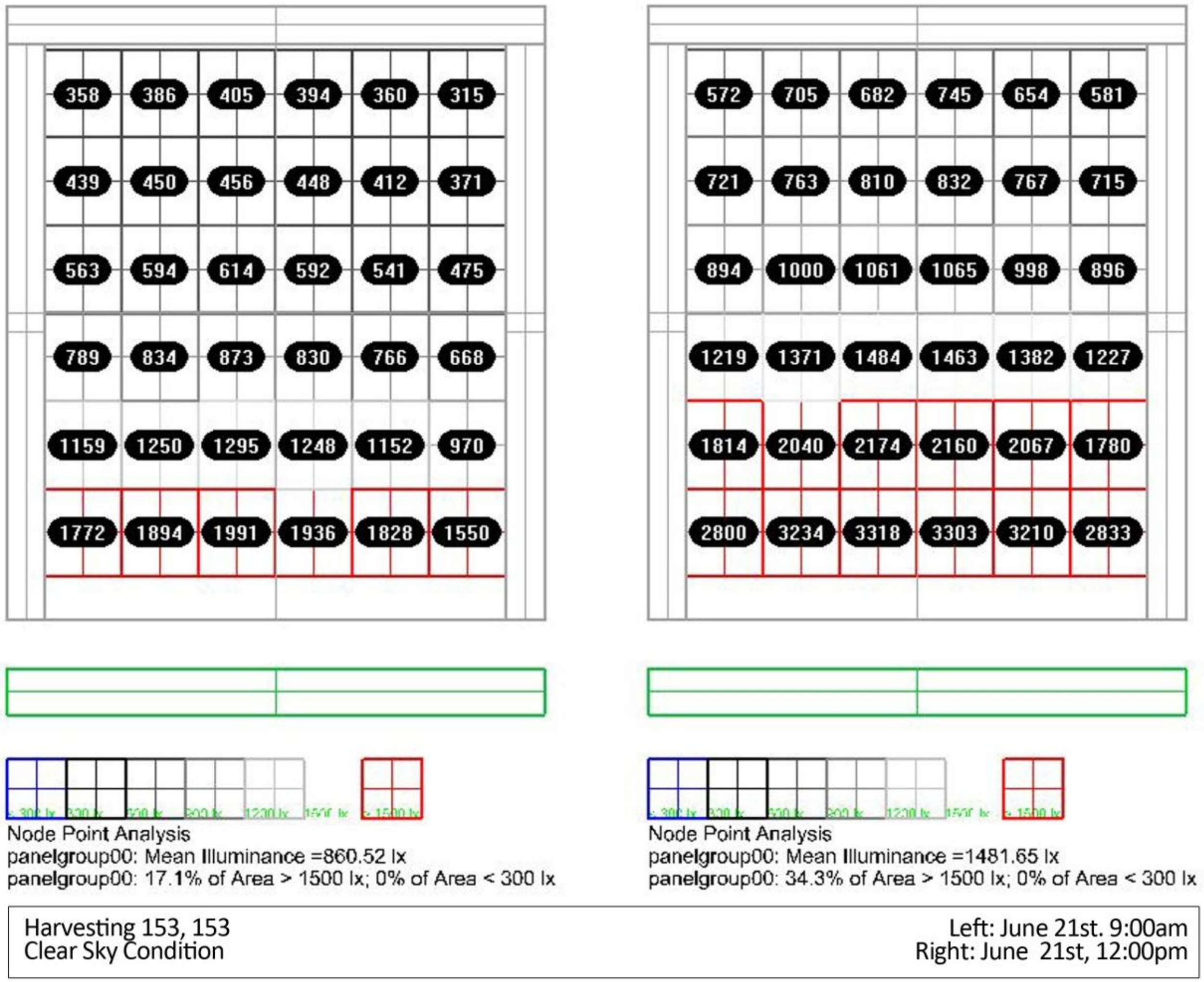


Figure 9-44: Harvesting 153° and 153° results - The figure shows the illuminance node values inside the space.

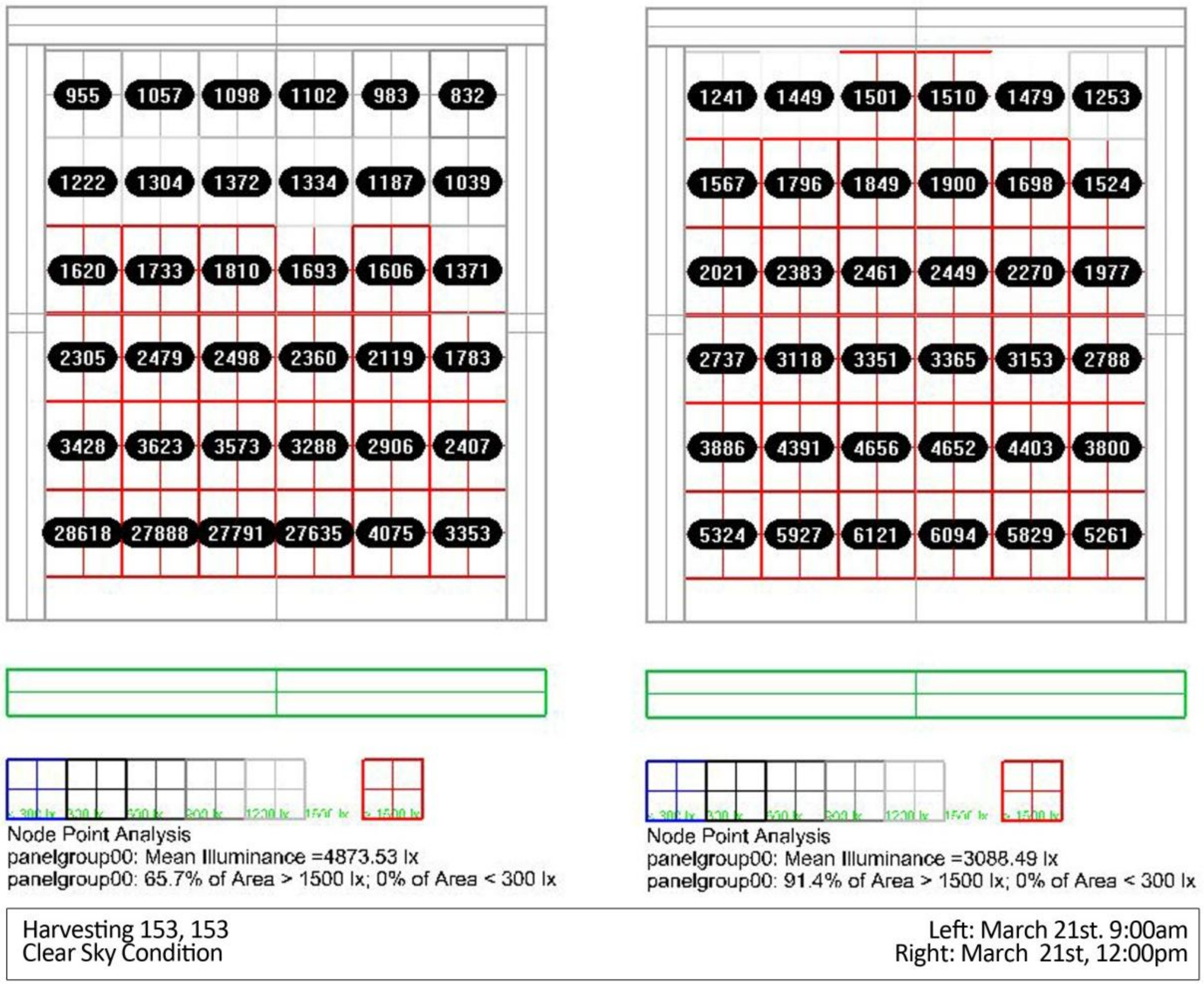


Figure 9-45: Harvesting 153° and 153° results - The figure shows the illuminance node values inside the space.

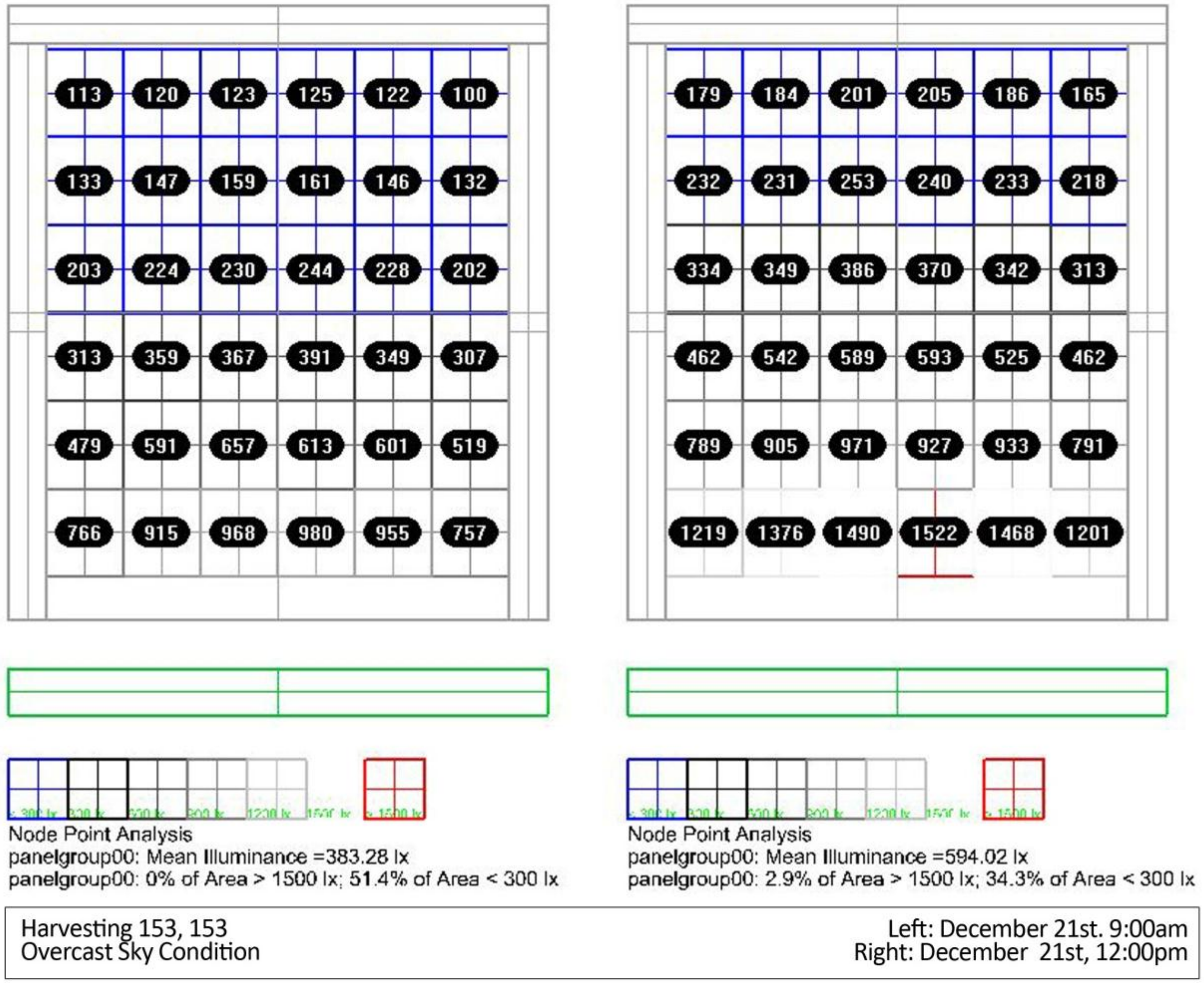


Figure 9-46: Harvesting 153° and 153° results - The figure shows the illuminance node values inside the space.

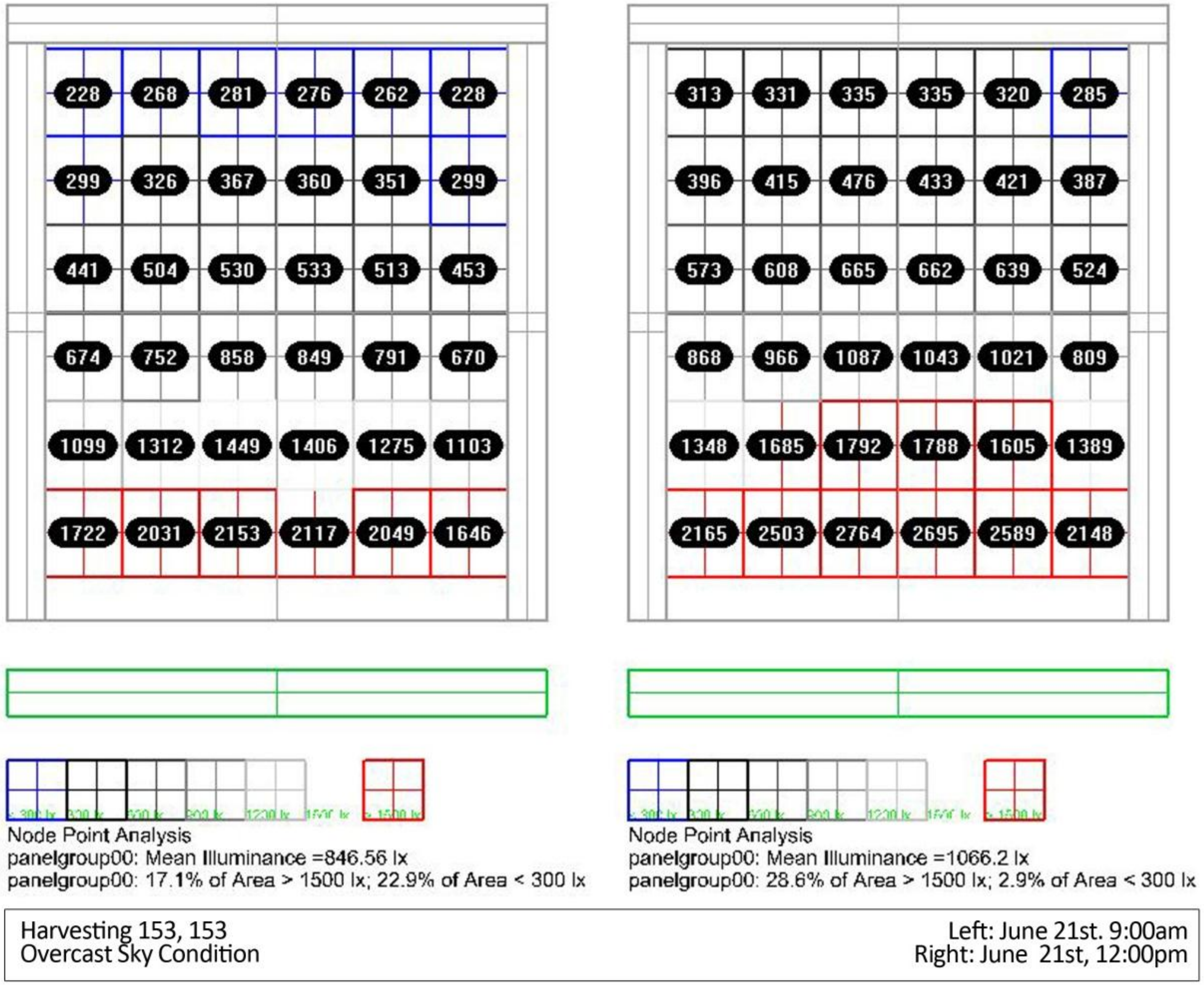


Figure 9-47: Harvesting 153° and 153° results - The figure shows the illuminance node values inside the space.

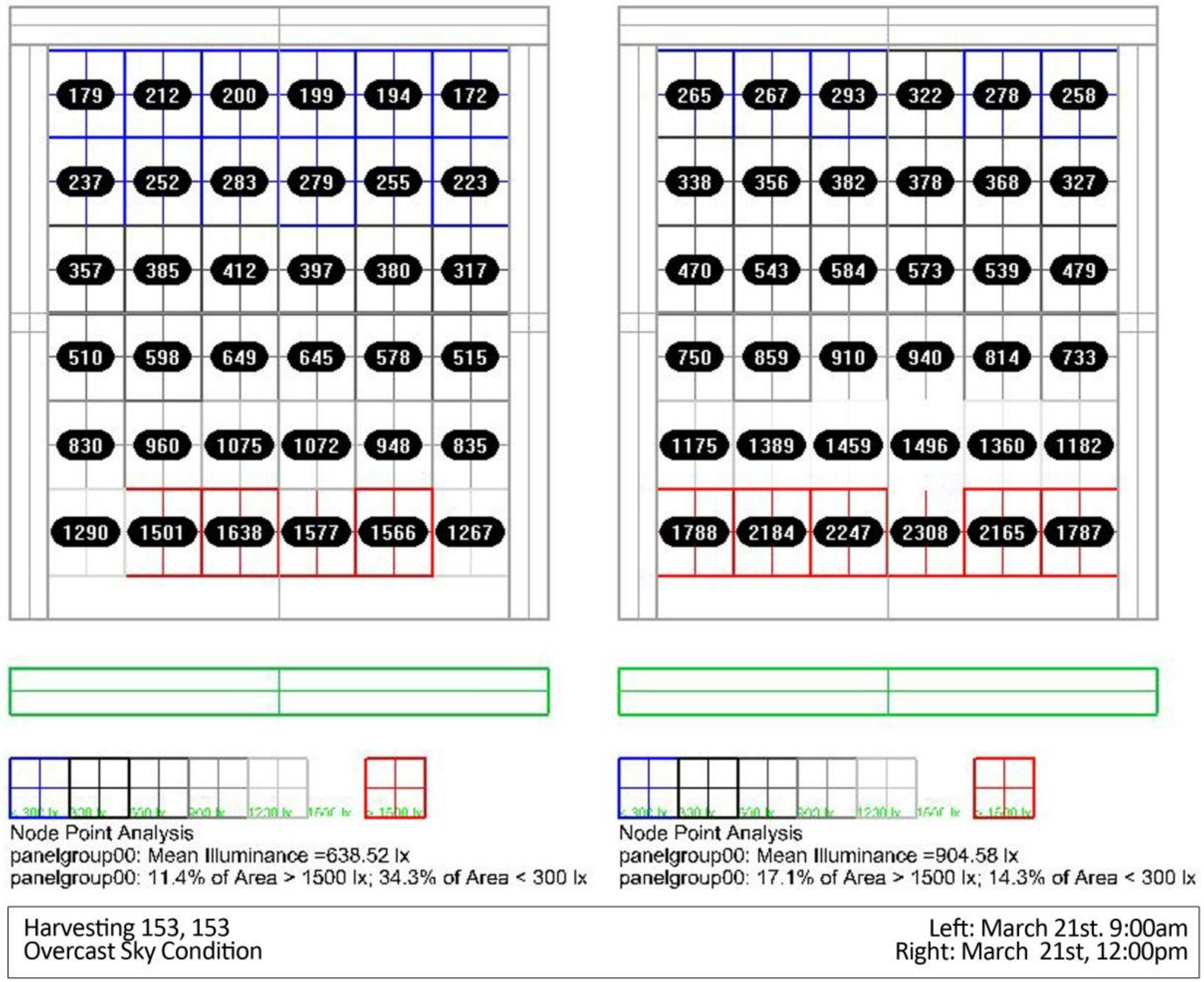


Figure 9-48: Harvesting 153° and 153° results - The figure shows the illuminance node values inside the space.

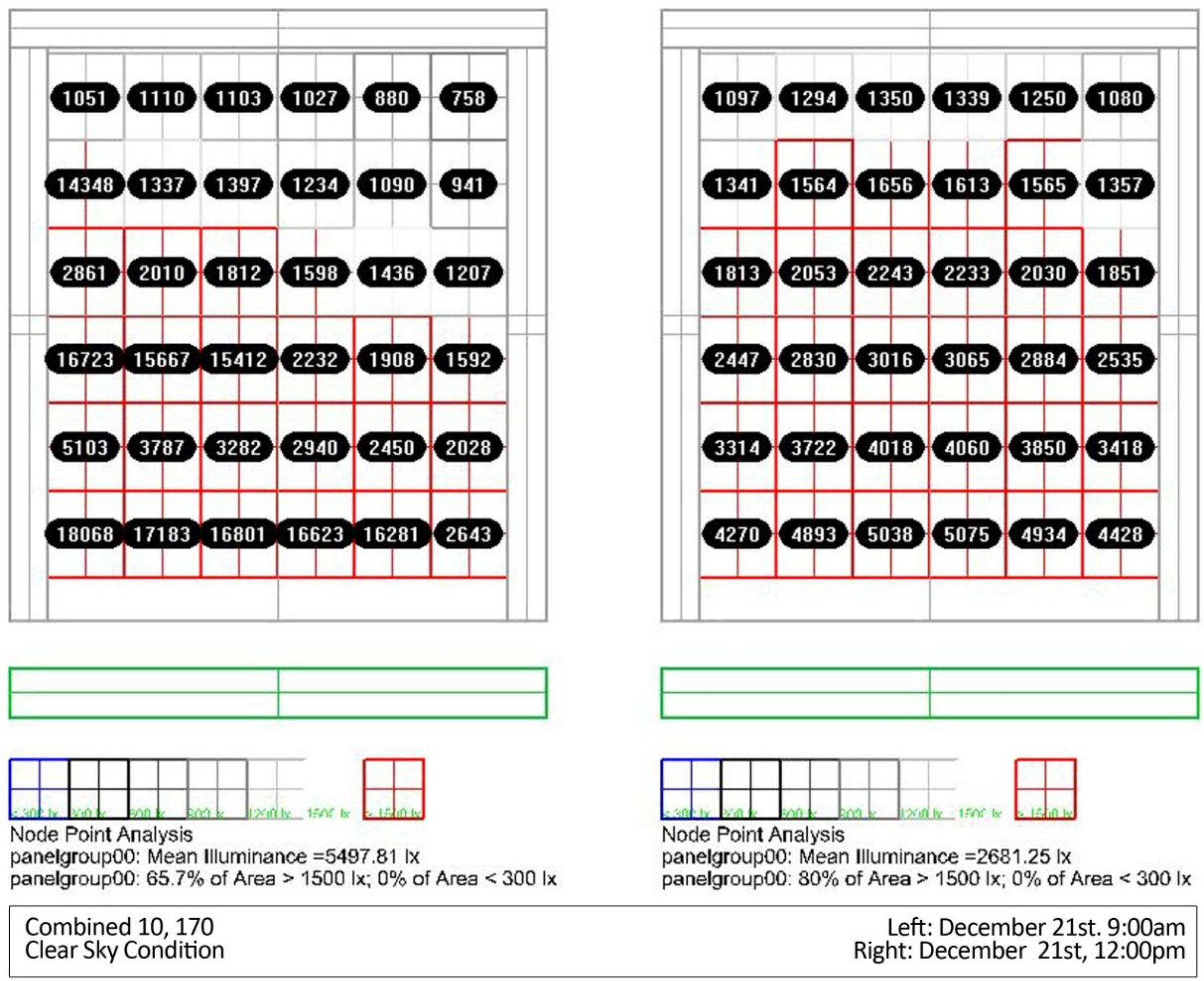


Figure 9-48: Combined 10° and 170° results - The figure shows the illuminance node values inside the space.

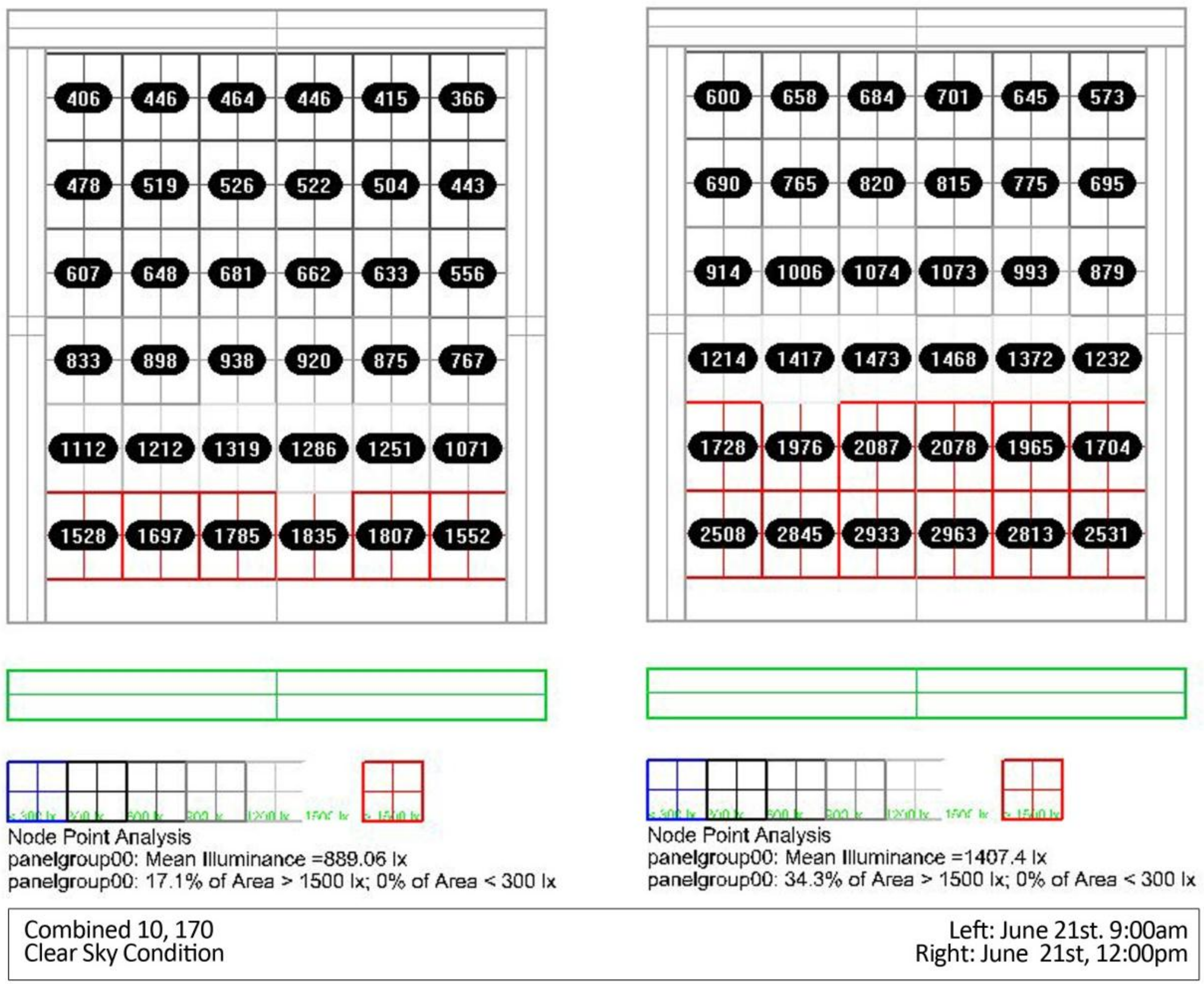


Figure 9-49: Combined 10° and 170° results - The figure shows the illuminance node values inside the space.

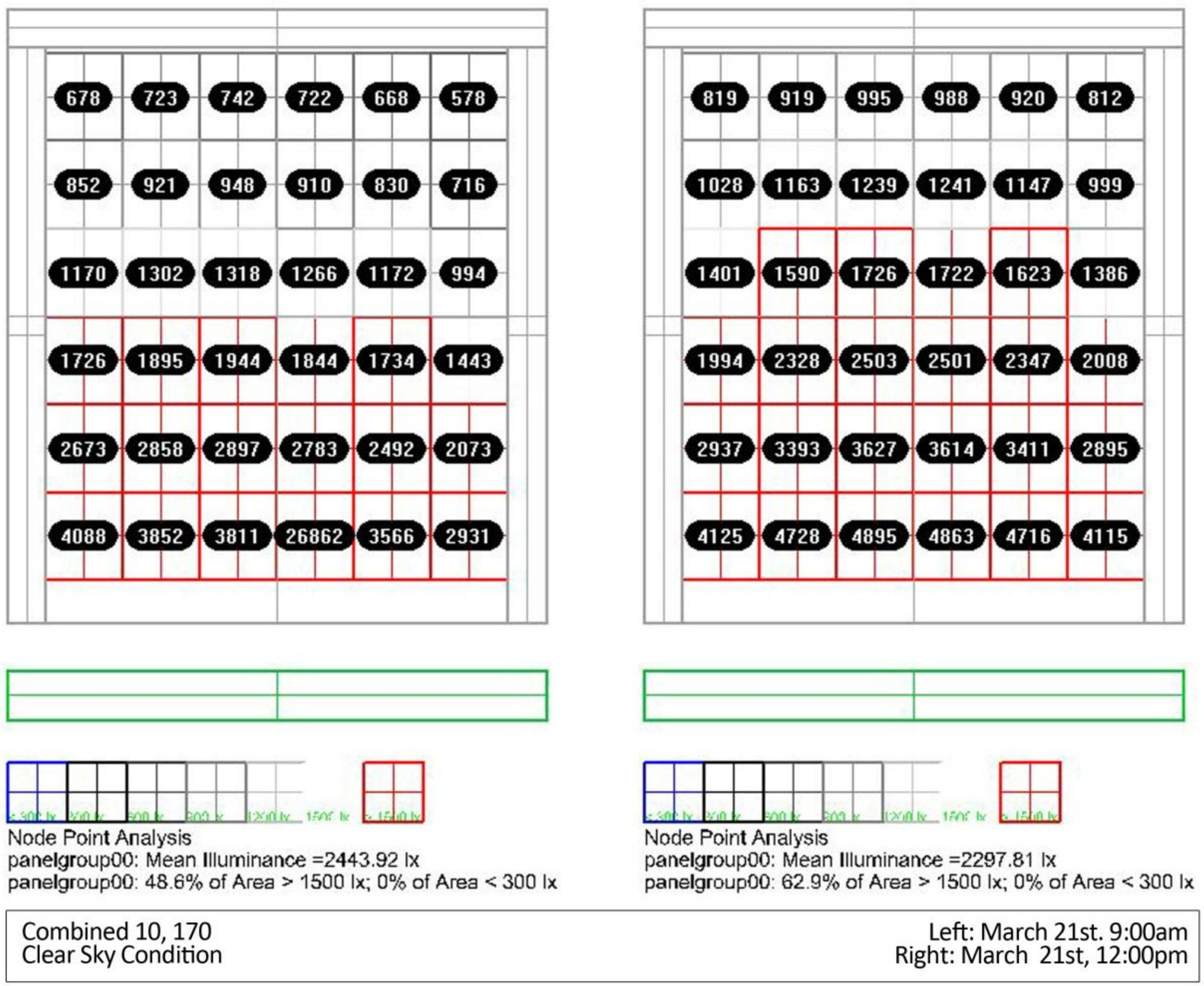


Figure 9-50: Combined 10° and 170° results - The figure shows the illuminance node values inside the space.

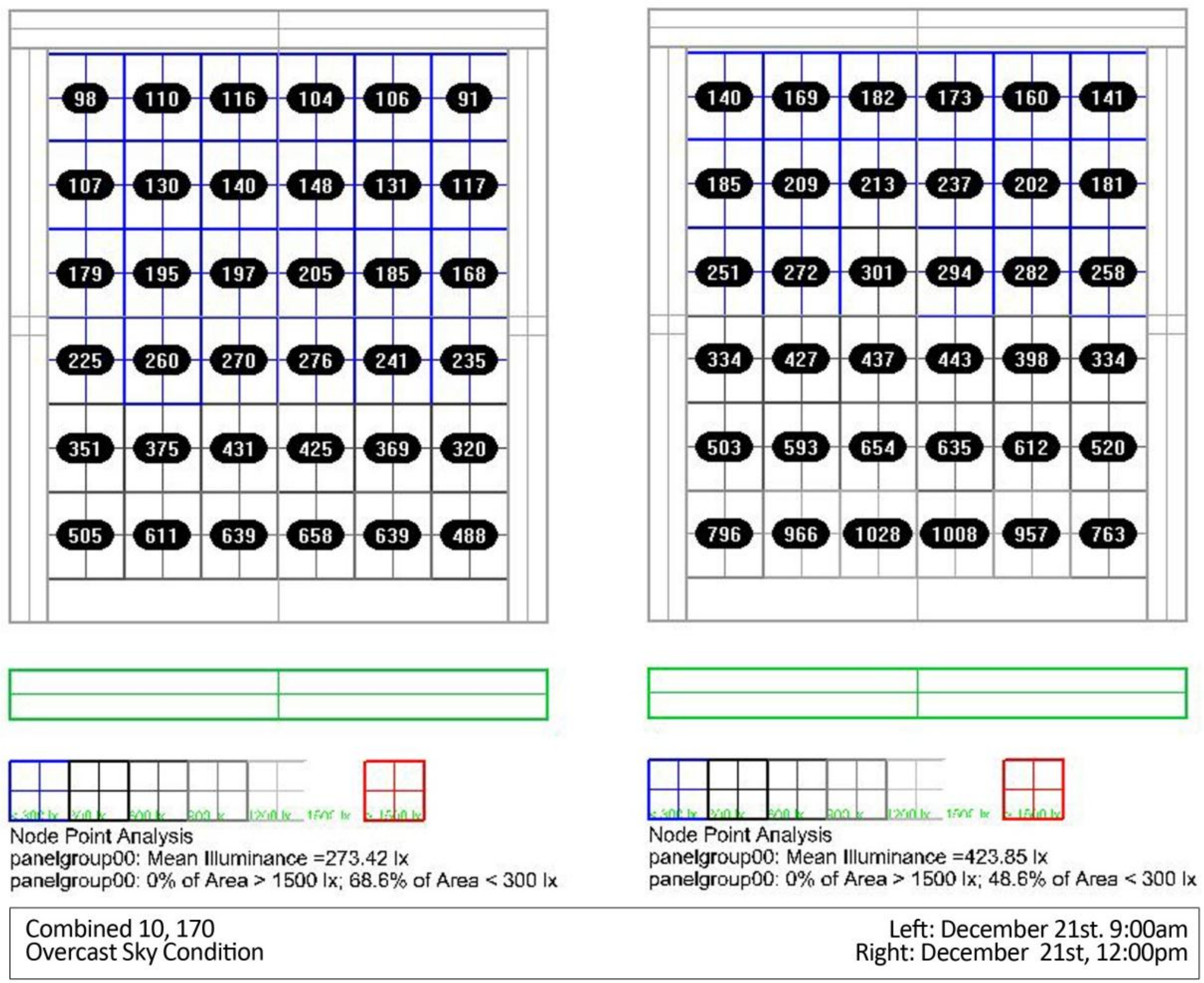


Figure 9-51: Combined 10° and 170° results - The figure shows the illuminance node values inside the space.

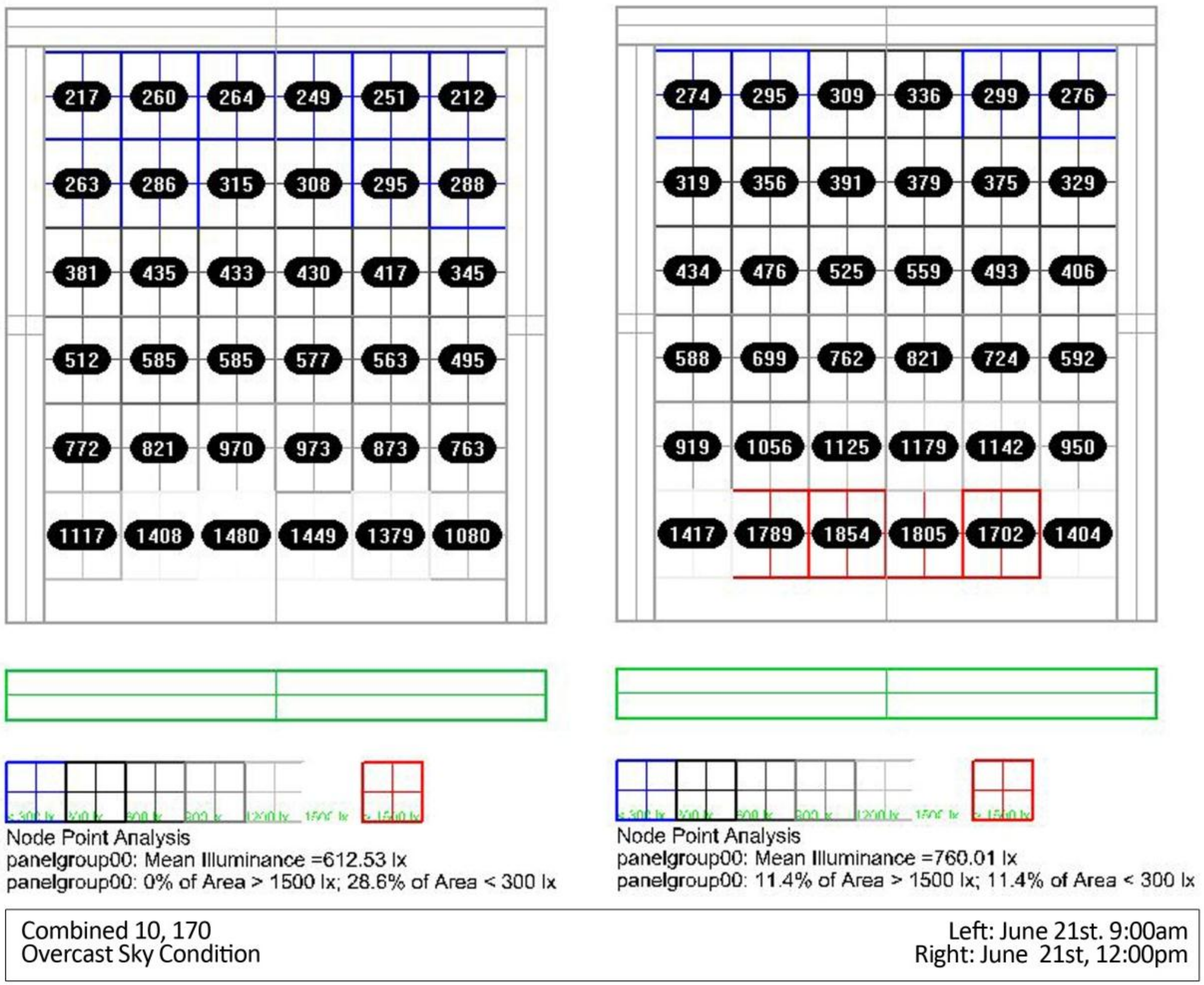


Figure 9-52: Combined 10° and 170° results - The figure shows the illuminance node values inside the space.

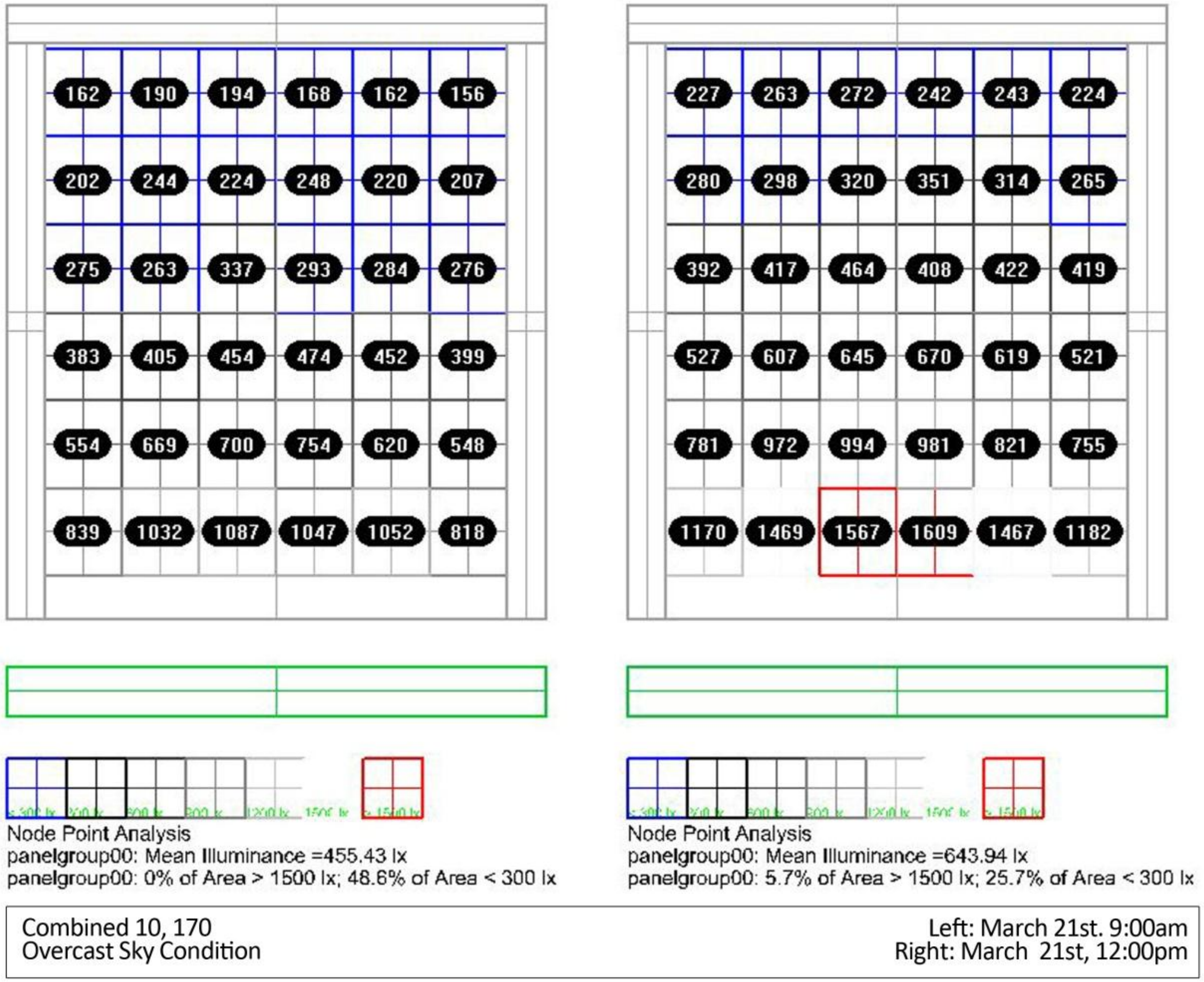


Figure 9-53: Combined 10° and 170° results - The figure shows the illuminance node values inside the space.

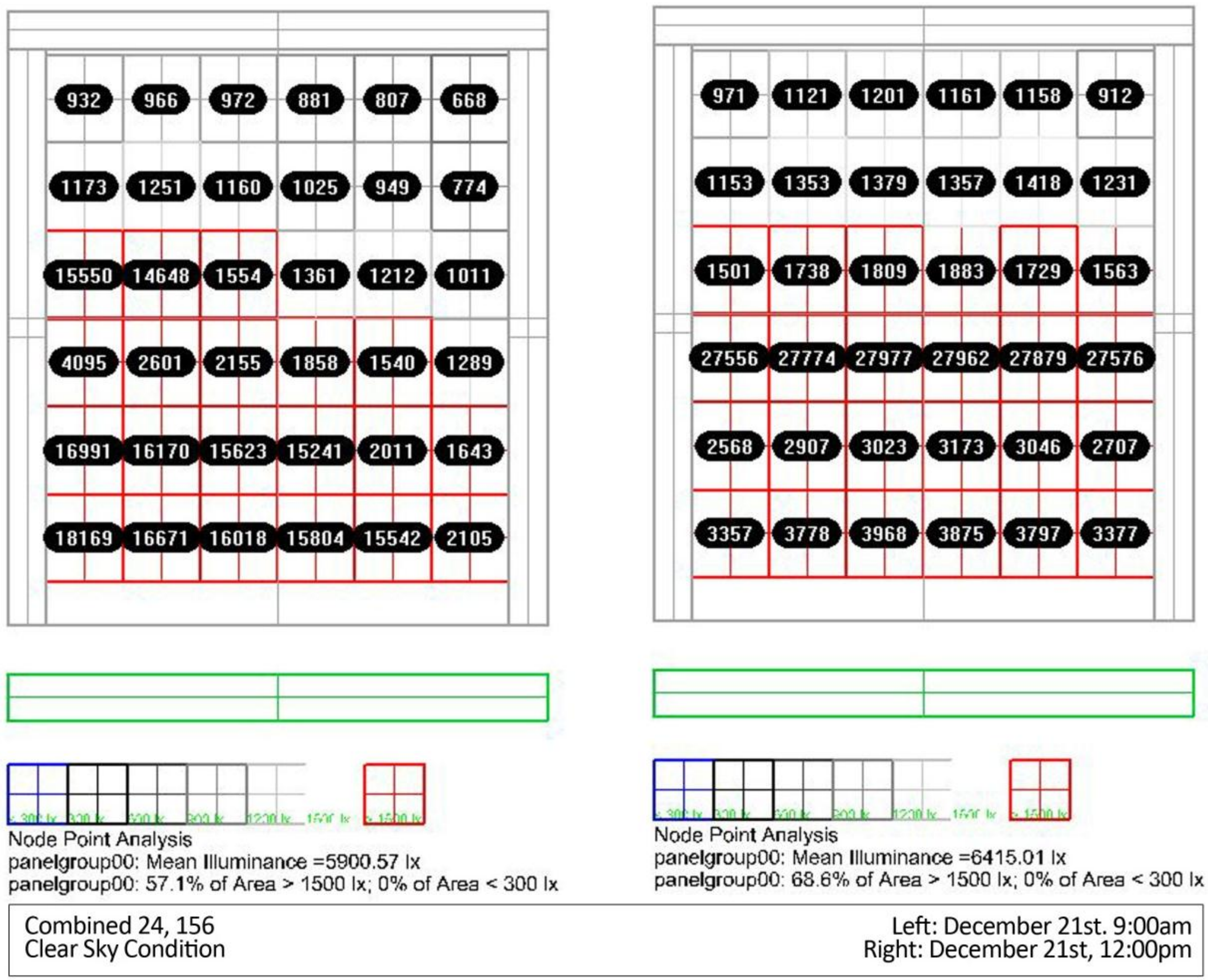


Figure 9-54: Combined 24° and 156° results - The figure shows the illuminance node values inside the space.

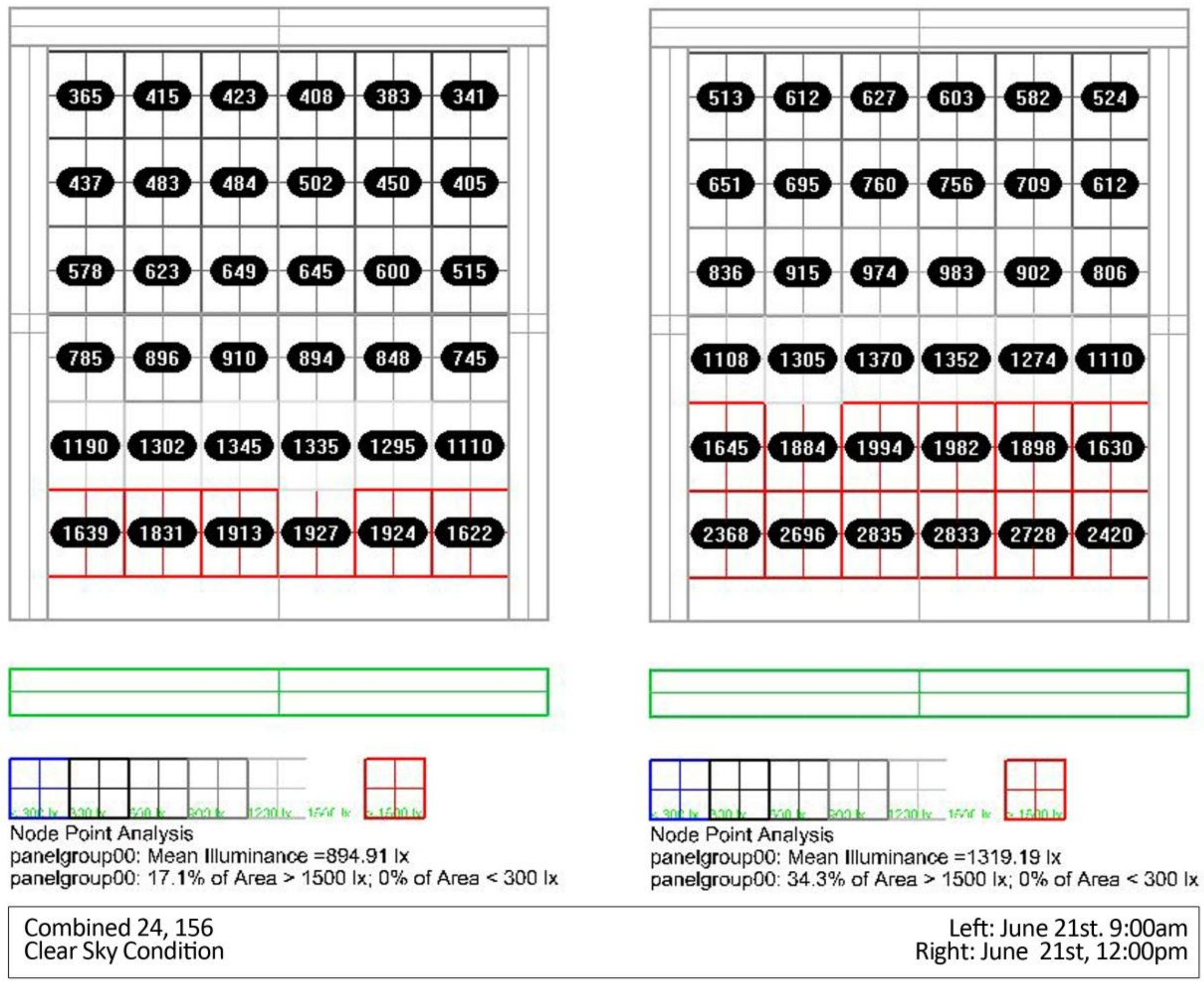


Figure 9-55: Combined 24° and 156° results - The figure shows the illuminance node values inside the space.

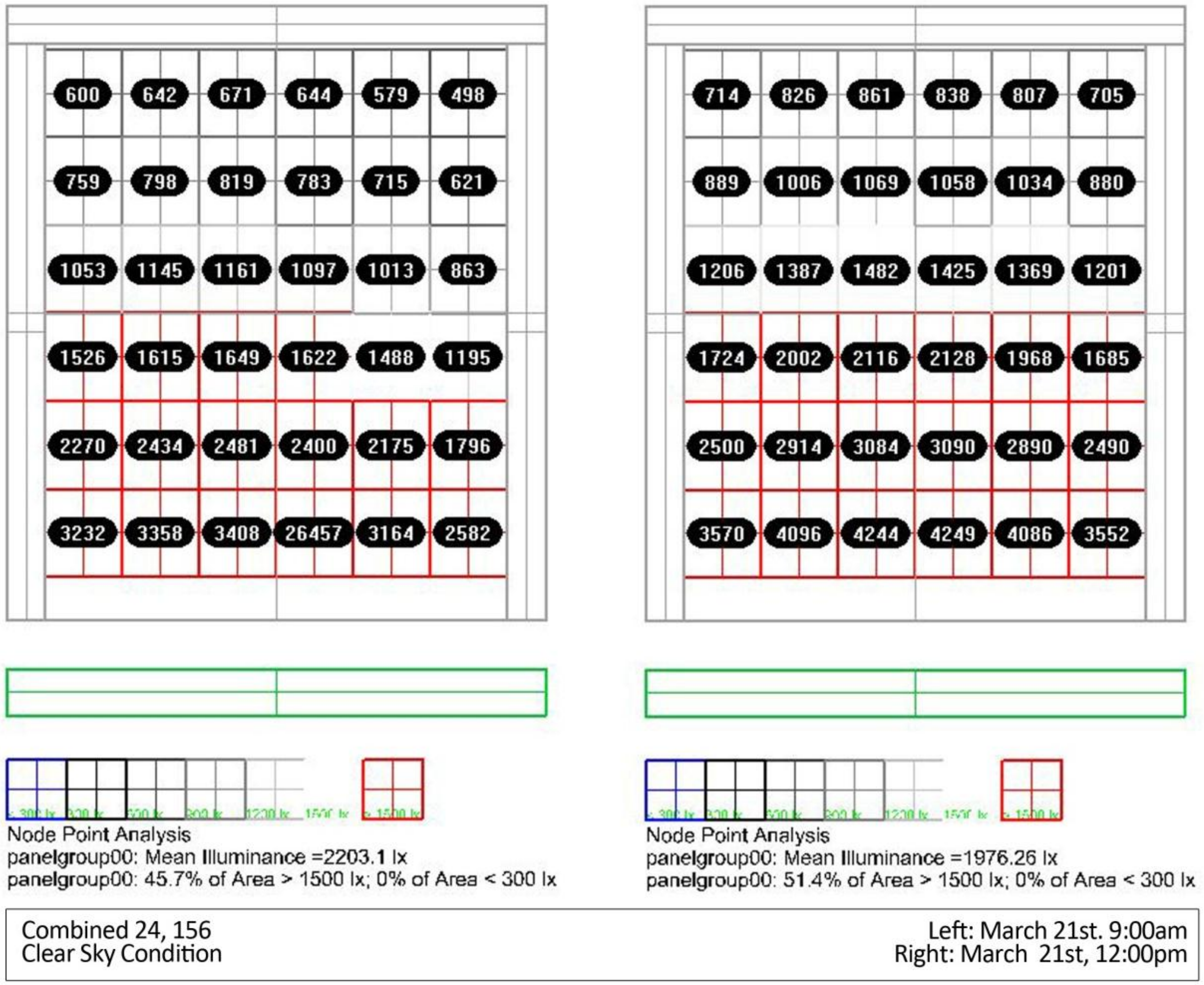


Figure 9-56: Combined 24° and 156° results - The figure shows the illuminance node values inside the space.

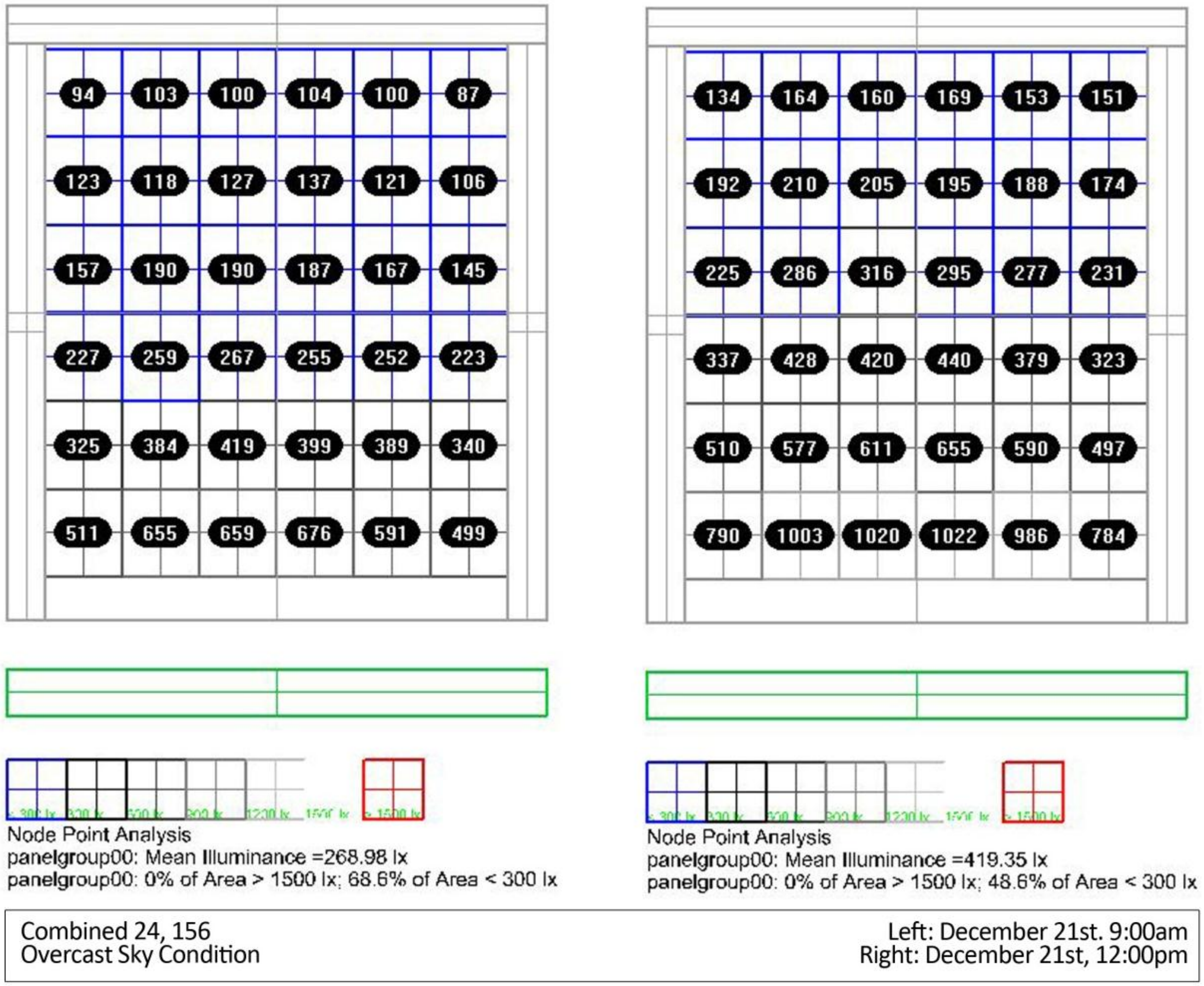


Figure 9-57: Combined 24° and 156° results - The figure shows the illuminance node values inside the space.

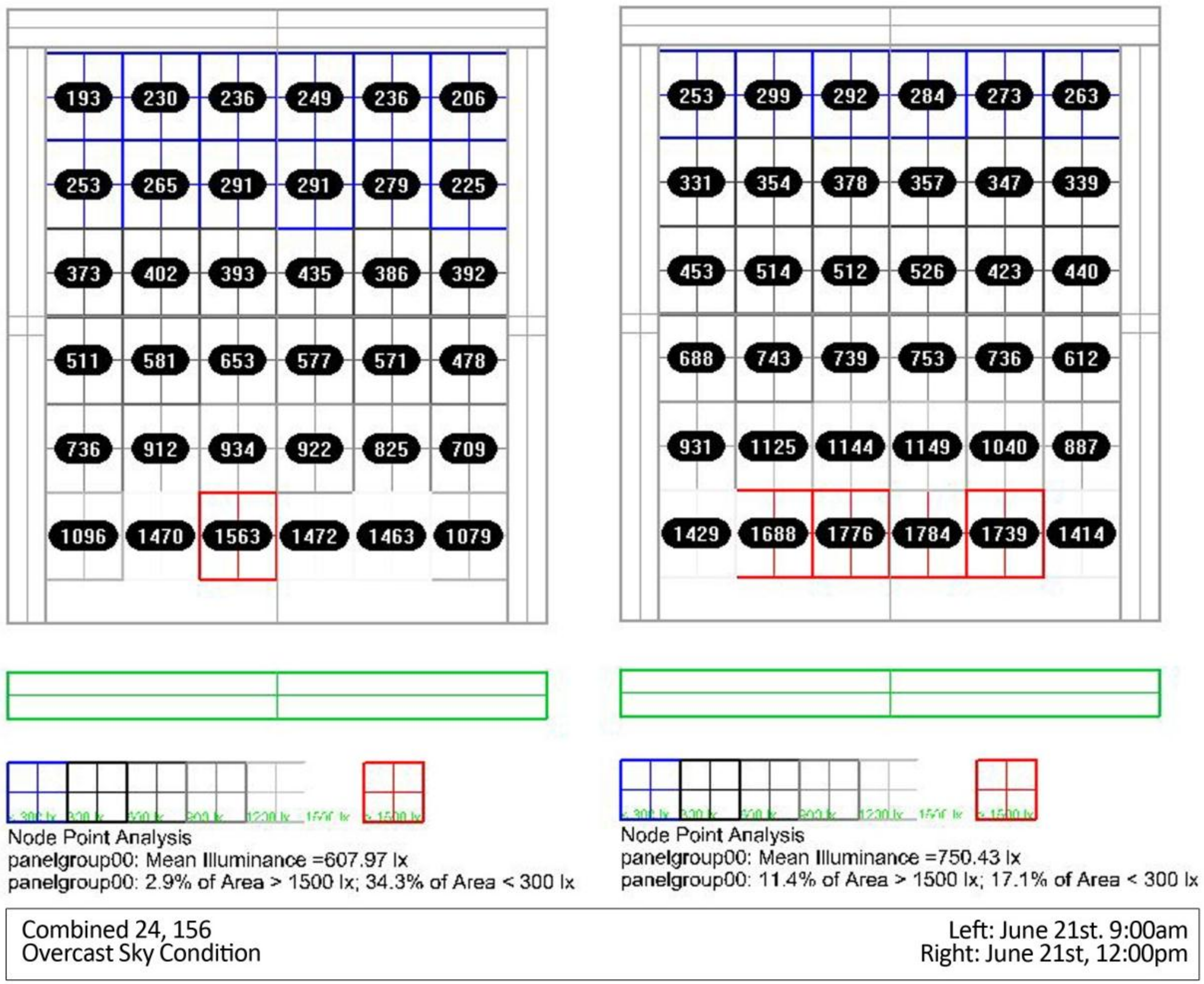


Figure 9-58: Combined 24° and 156° results - The figure shows the illuminance node values inside the space.

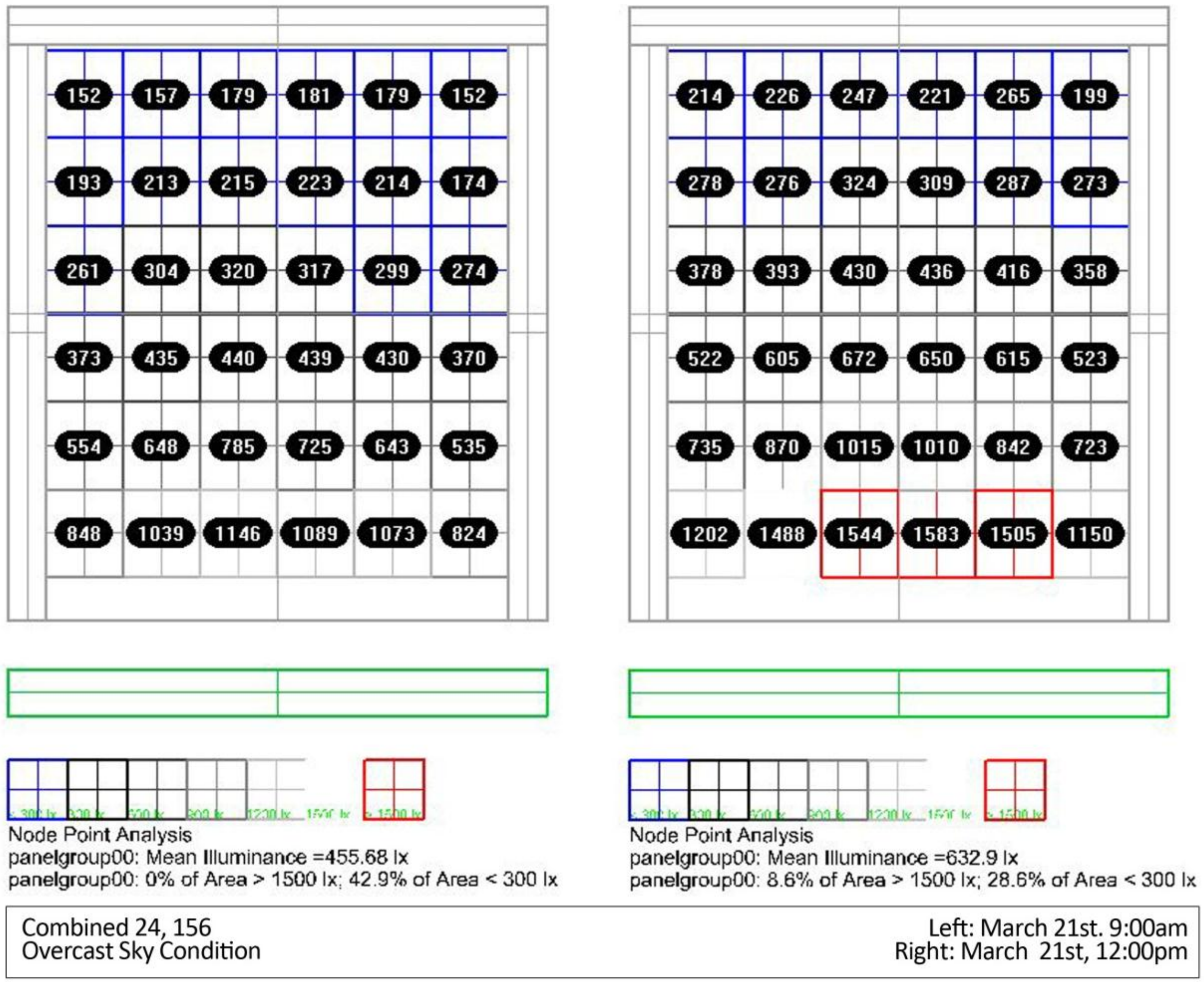


Figure 9-59: Combined 24° and 156° results - The figure shows the illuminance node values inside the space.

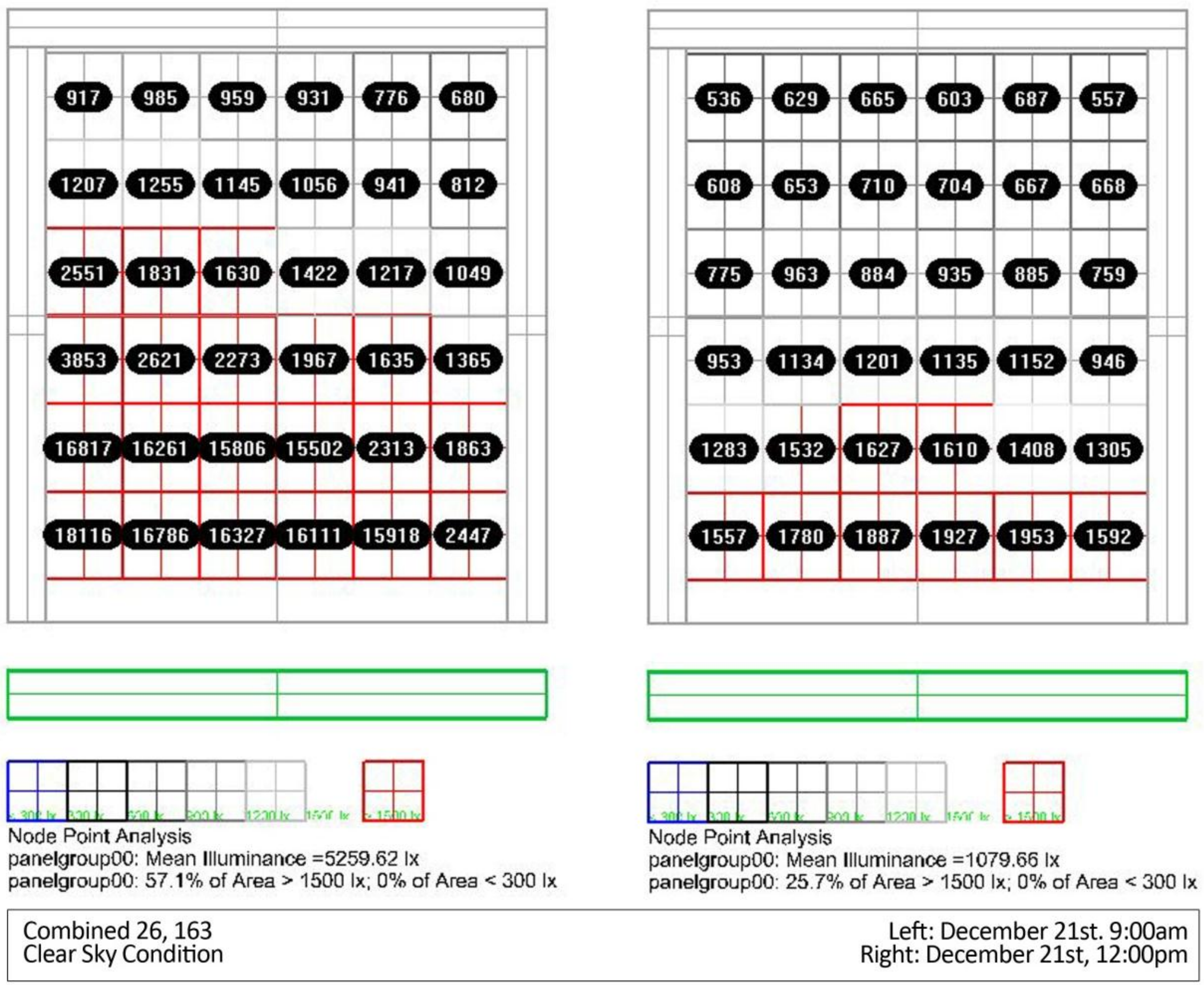


Figure 9-60: Combined 26° and 163° results - The figure shows the illuminance node values inside the space.

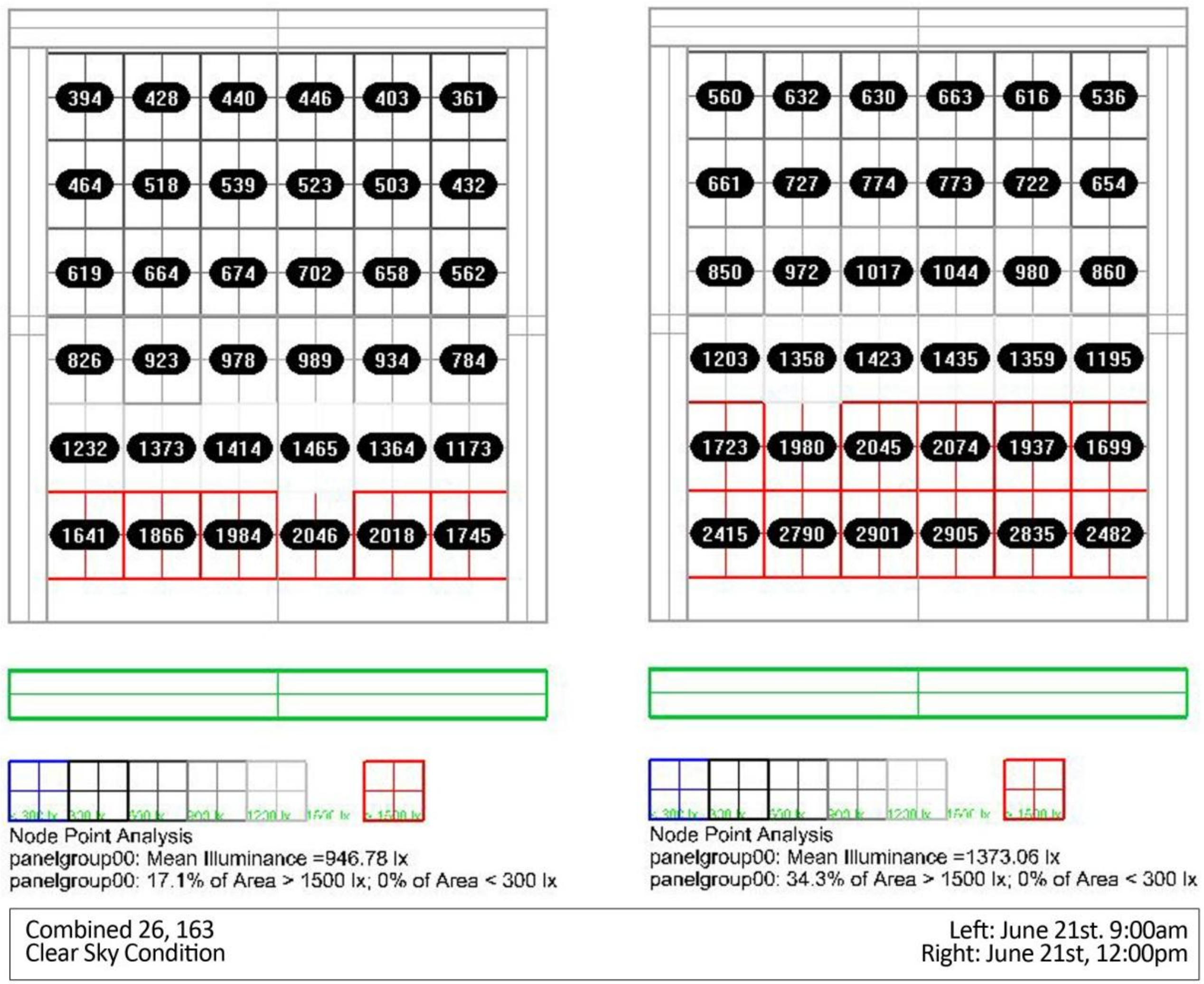


Figure 9-61: Combined 26° and 163° results - The figure shows the illuminance node values inside the space.

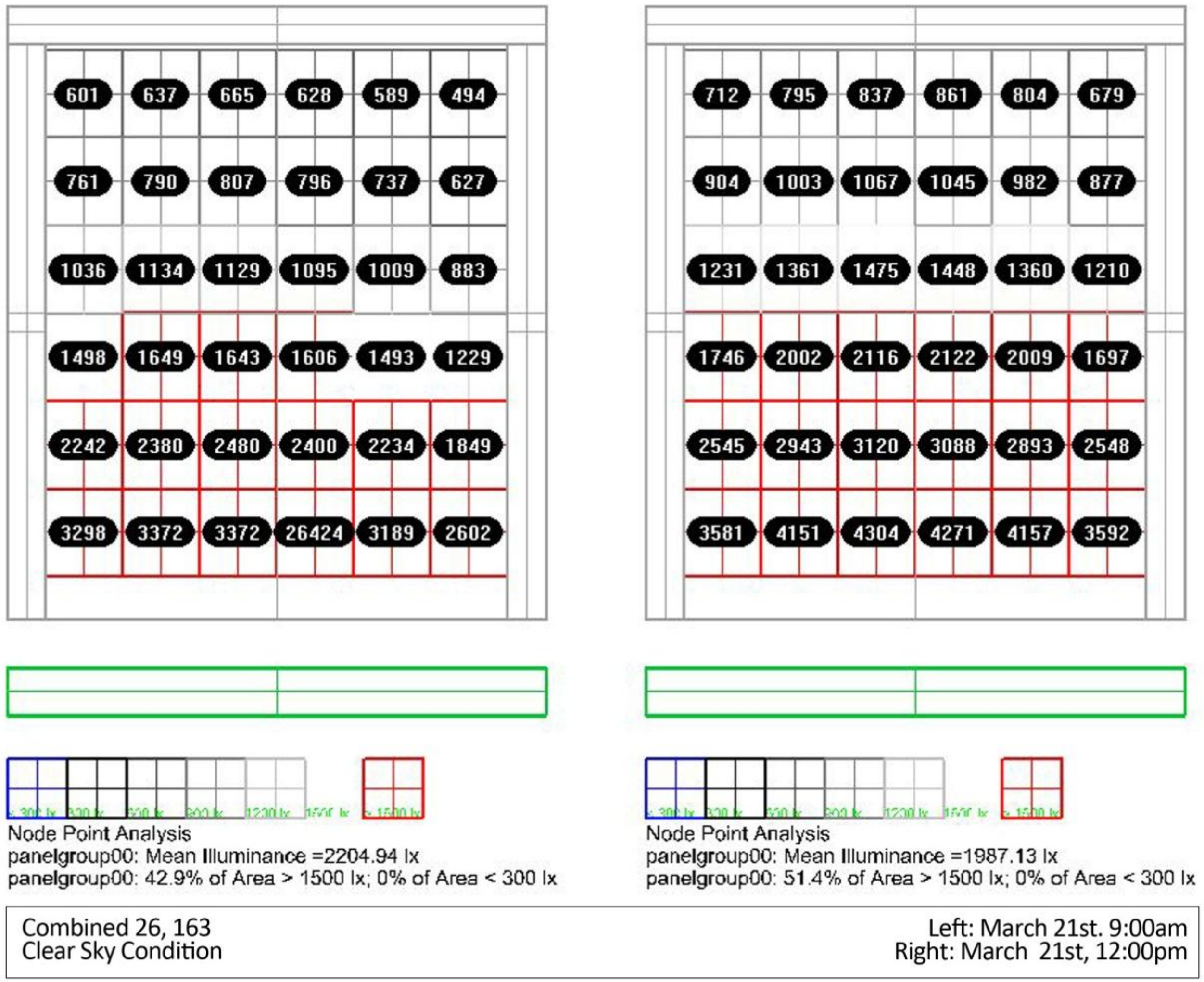


Figure 9-62: Combined 26° and 163° results - The figure shows the illuminance node values inside the space.

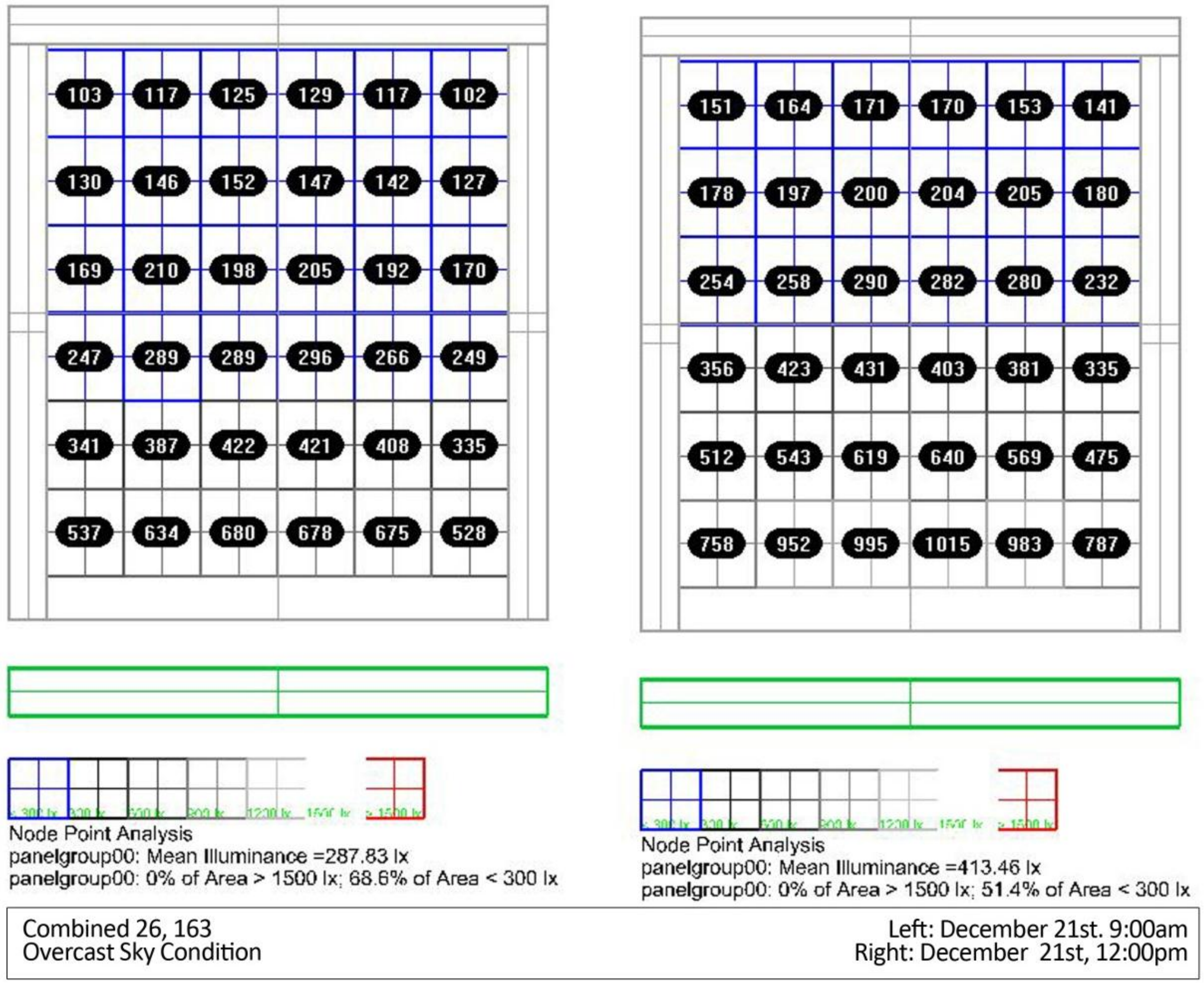


Figure 9-63: Combined 26° and 163° results - The figure shows the illuminance node values inside the space.

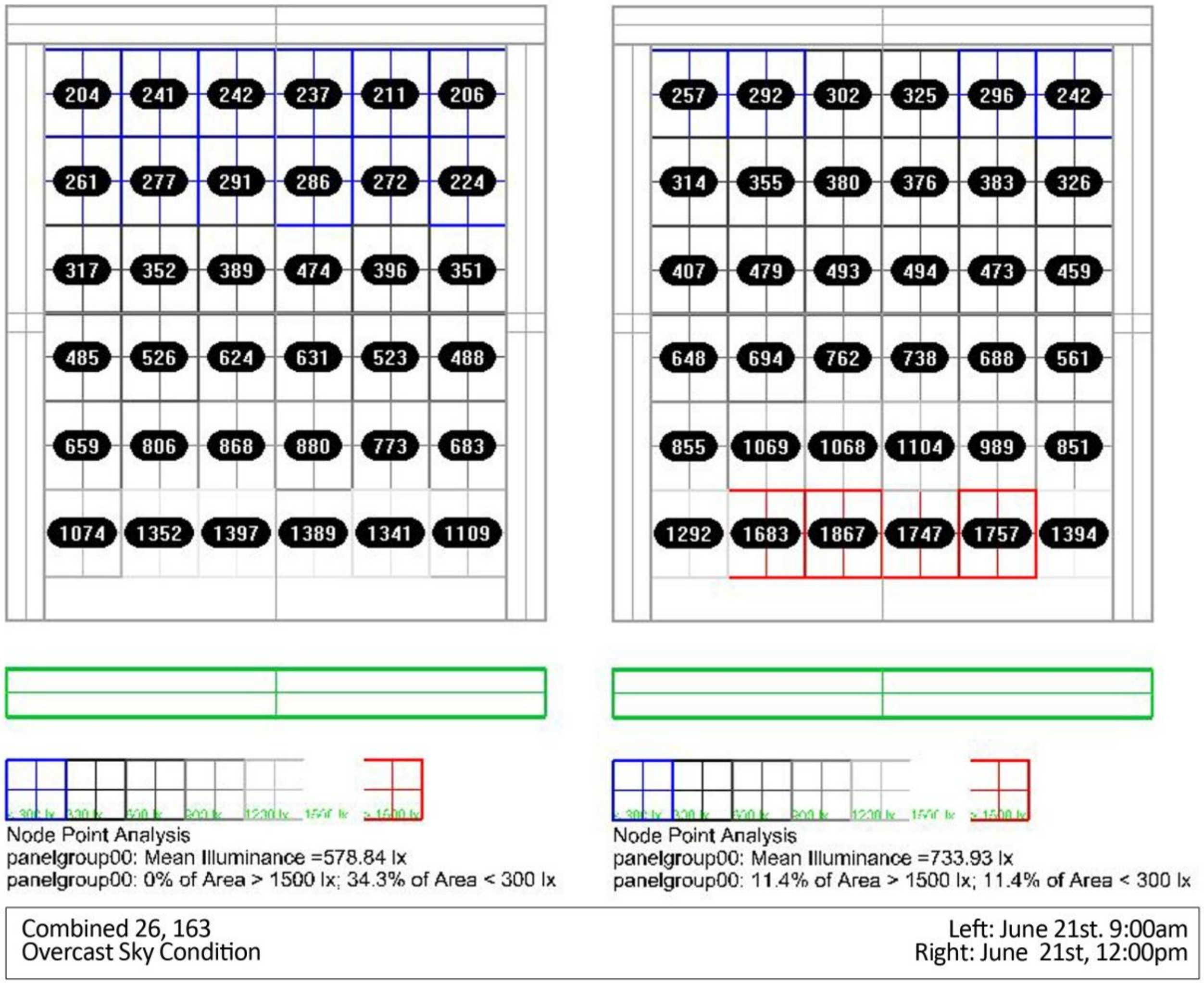


Figure 9-64: Combined 26° and 163° results - The figure shows the illuminance node values inside the space.

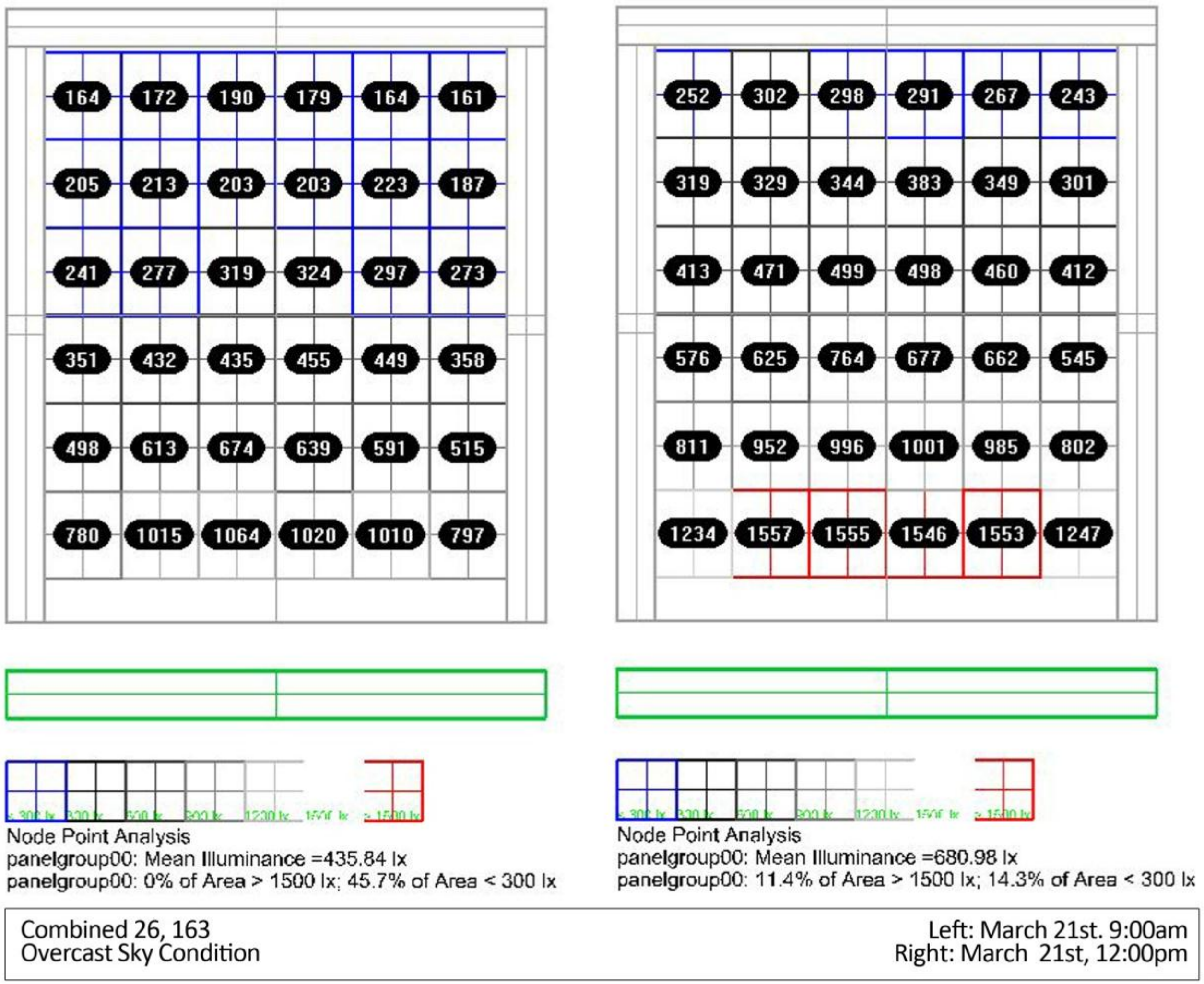
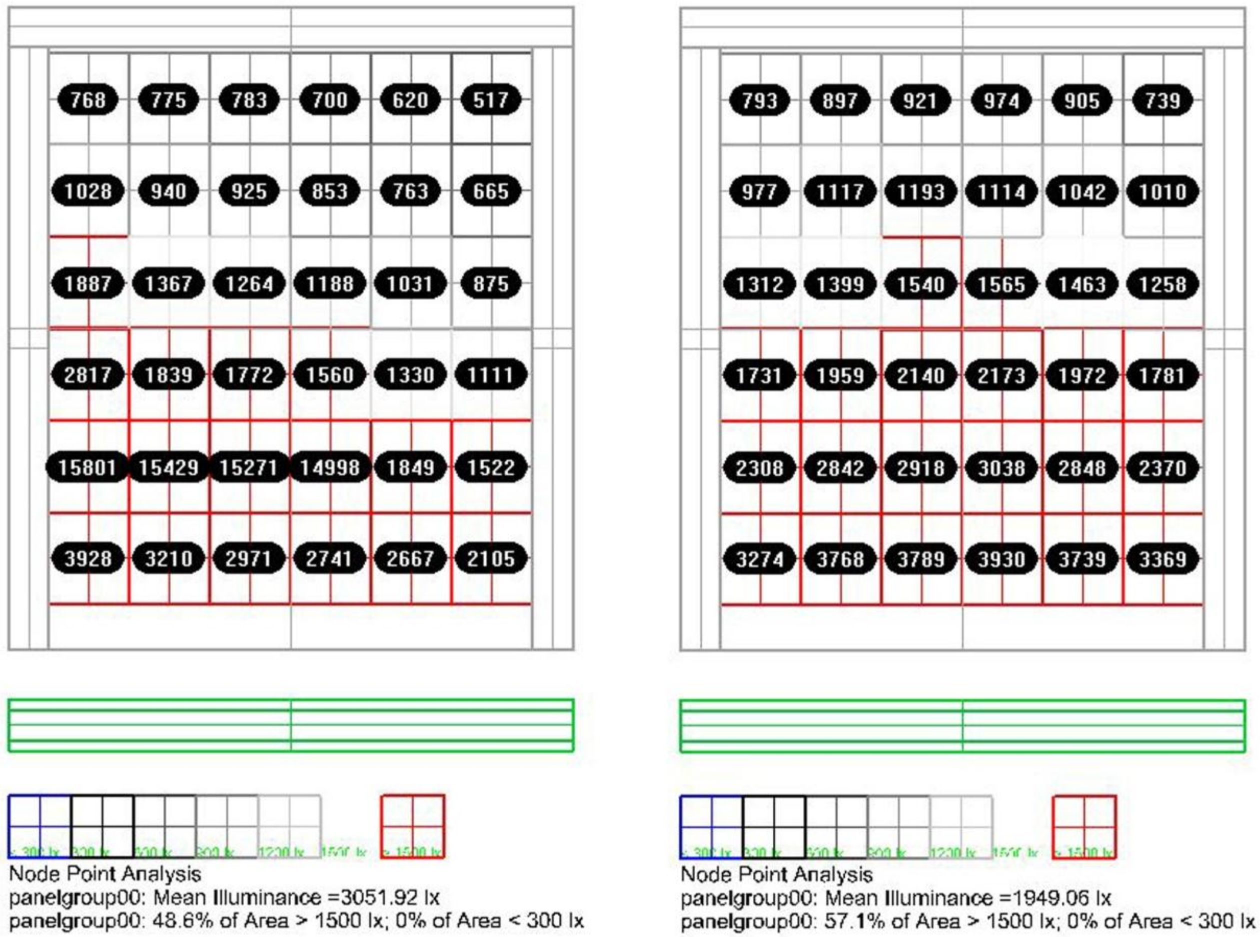


Figure 9-65: Combined 26° and 163° results - The figure shows the illuminance node values inside the space.



Combined 55,168
Clear Sky Condition

Left: December 21st. 9:00am
Right: December 21st, 12:00pm

Figure 9-66: Combined 55° and 168° results - The figure shows the illuminance node values inside the space.

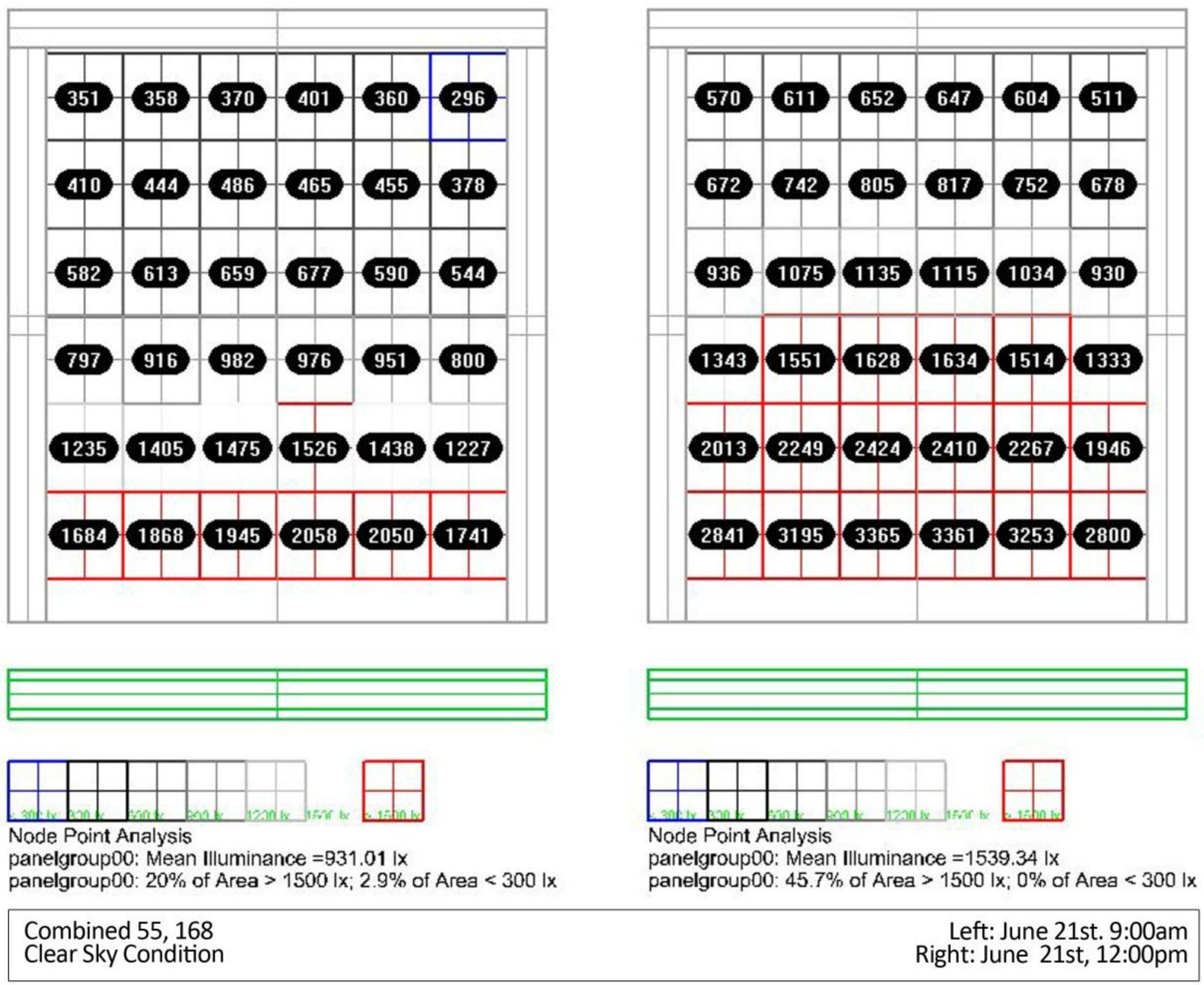


Figure 9-67: Combined 55° and 168° results - The figure shows the illuminance node values inside the space.

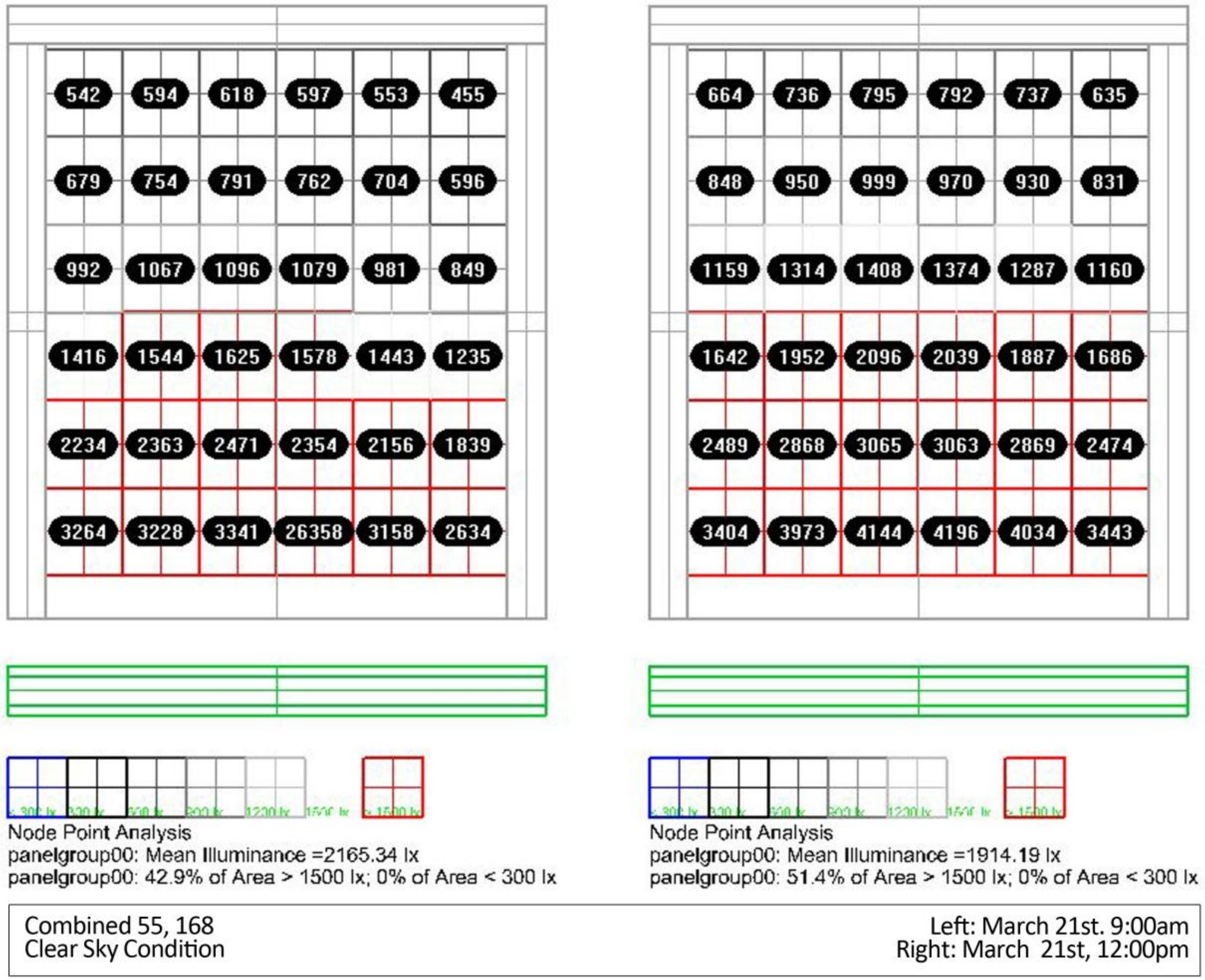


Figure 9-68: Combined 55° and 168° results - The figure shows the illuminance node values inside the space.

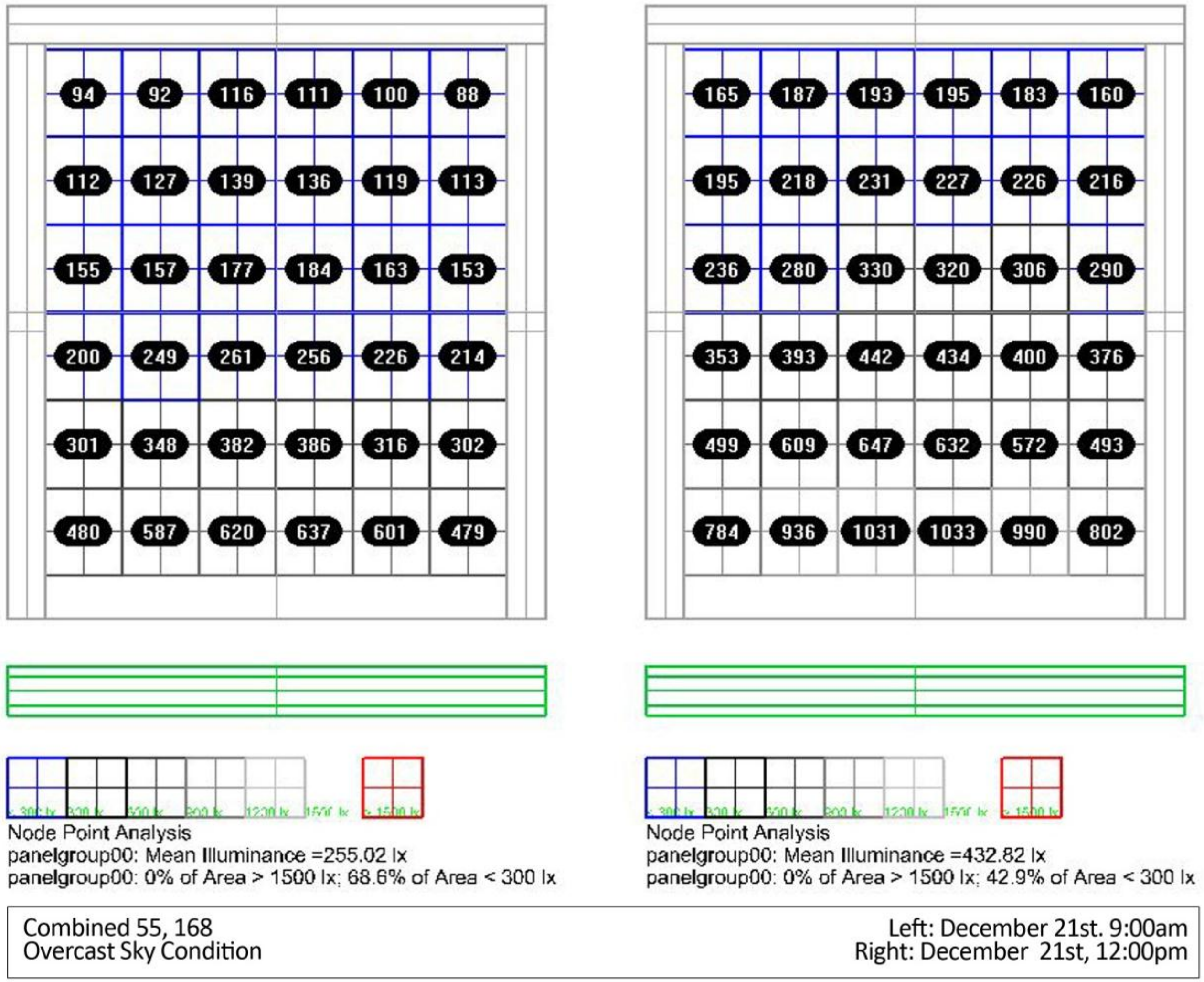


Figure 9-69: Combined 55° and 168° results - The figure shows the illuminance node values inside the space.

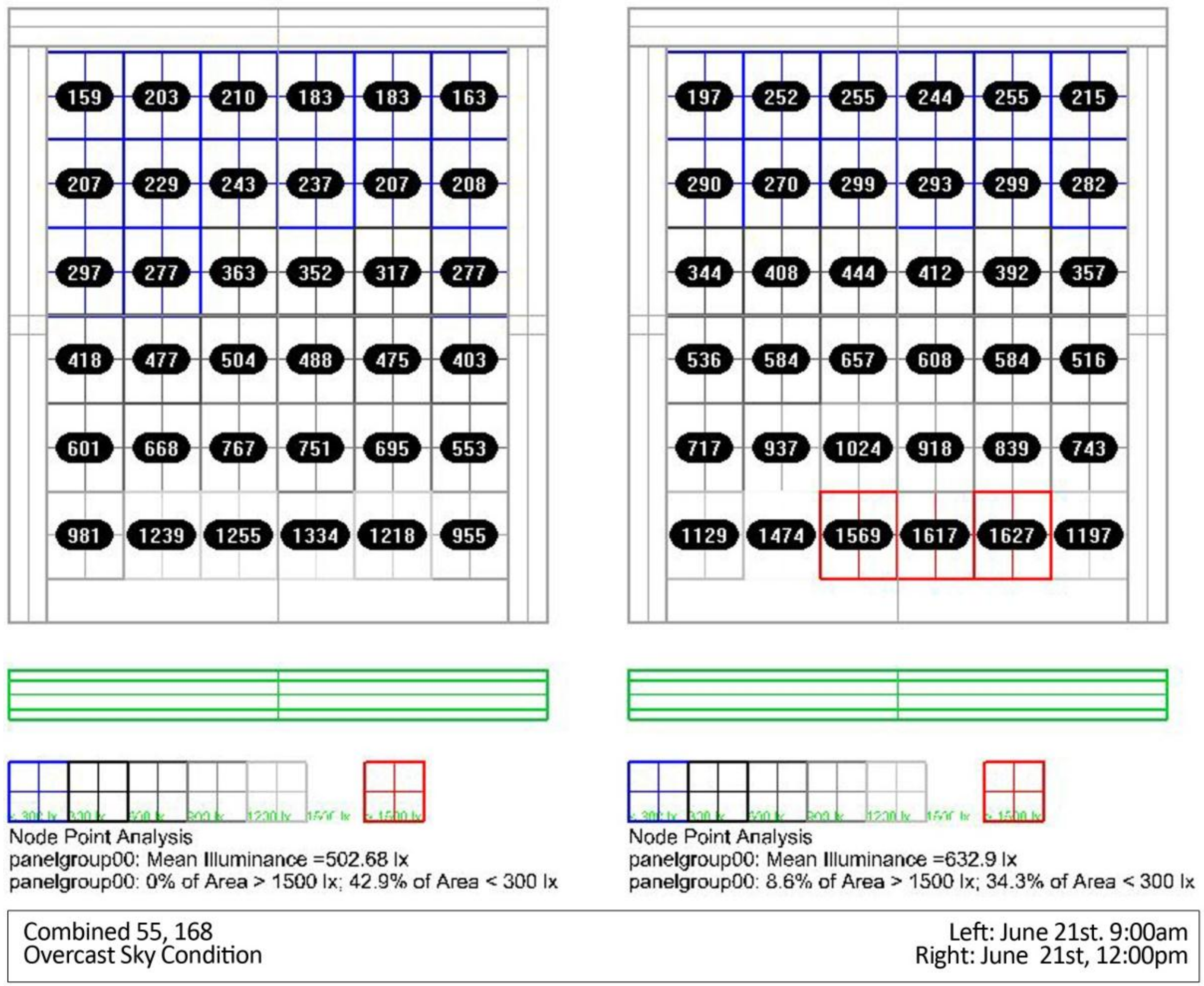


Figure 9-70: Combined 55° and 168° results - The figure shows the illuminance node values inside the space.

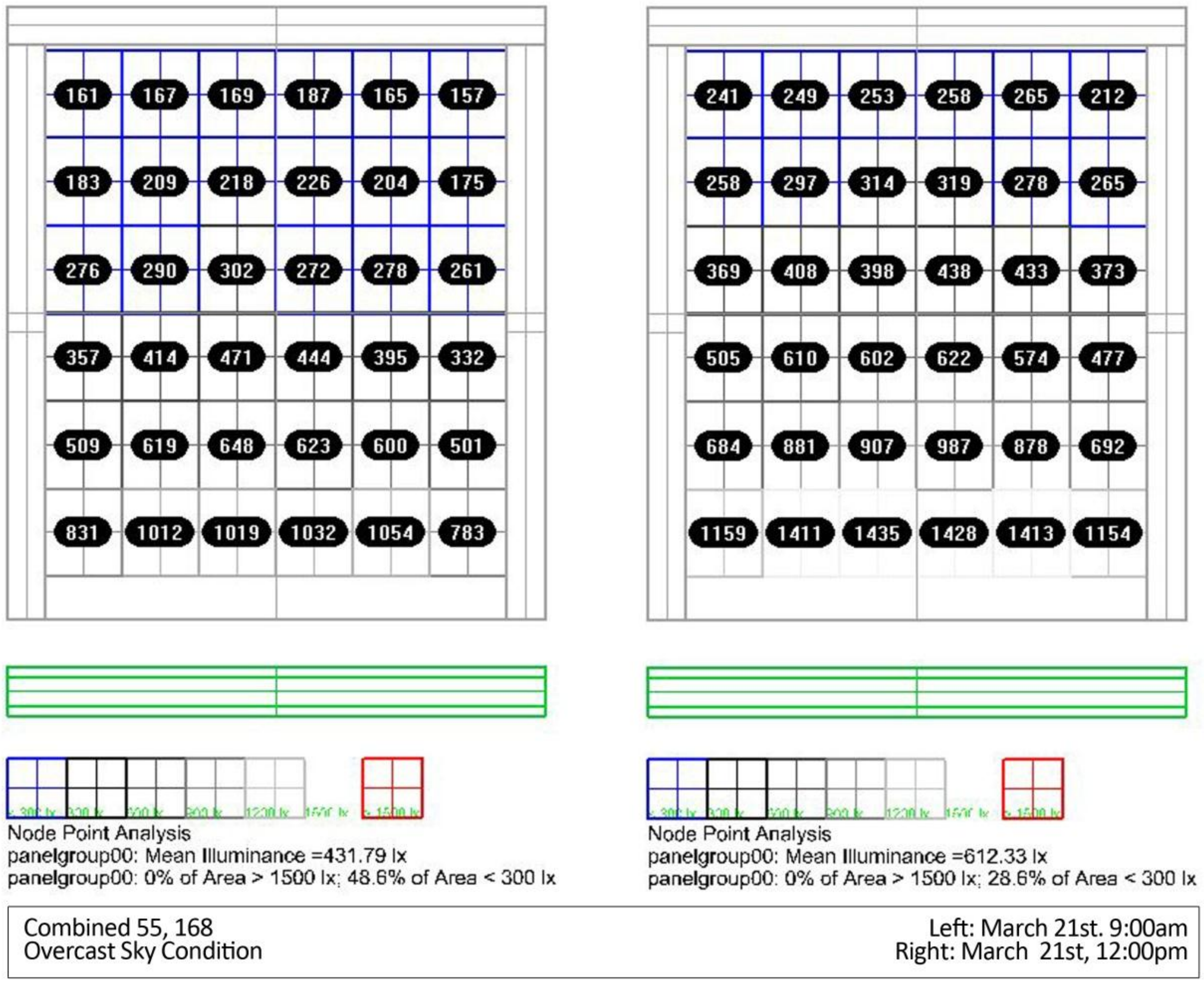


Figure 9-71: Combined 55° and 168° results - The figure shows the illuminance node values inside the space.

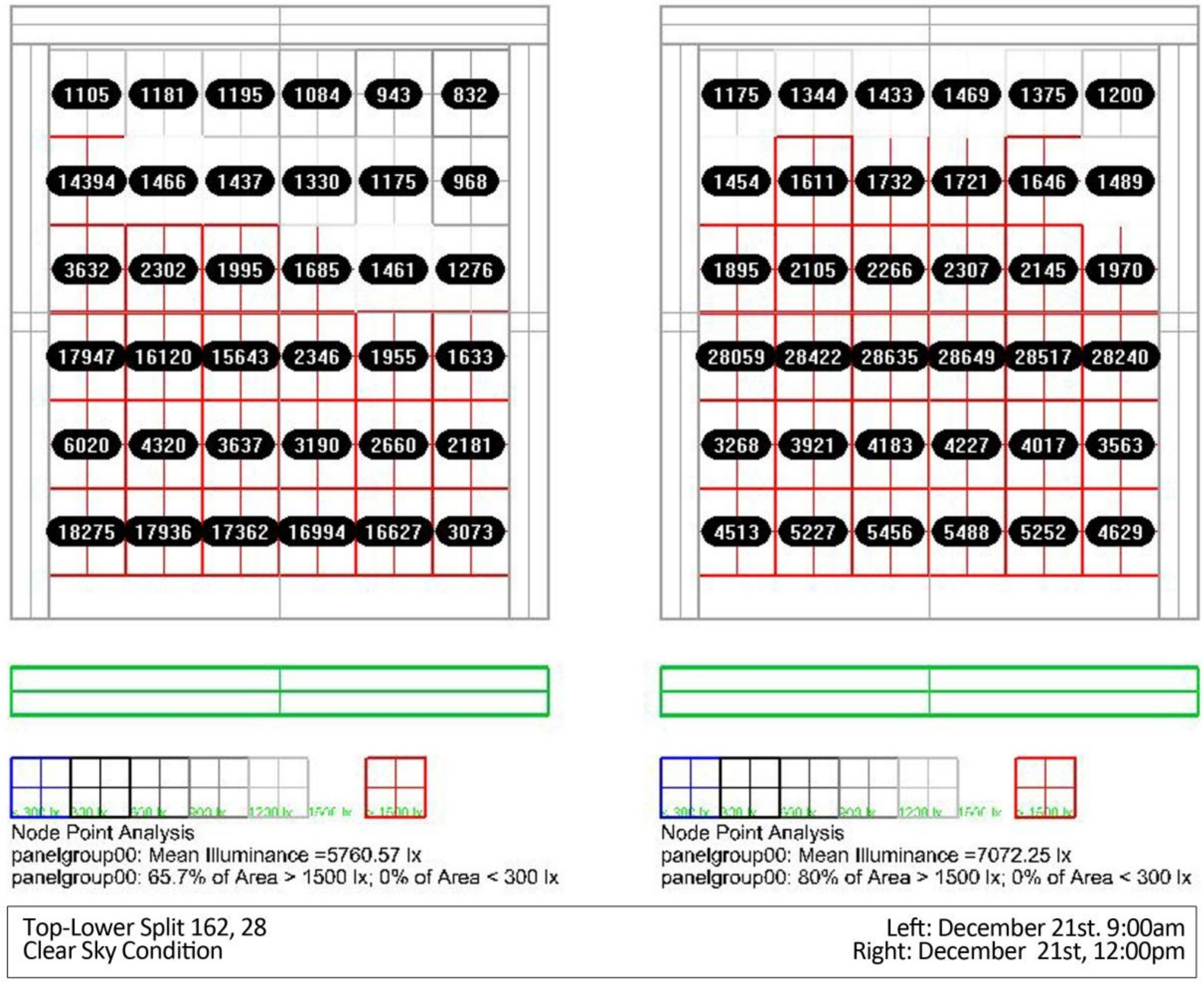


Figure 9-72: Top-lower split 162° and 28° results - The figure shows the illuminance node values inside the space.

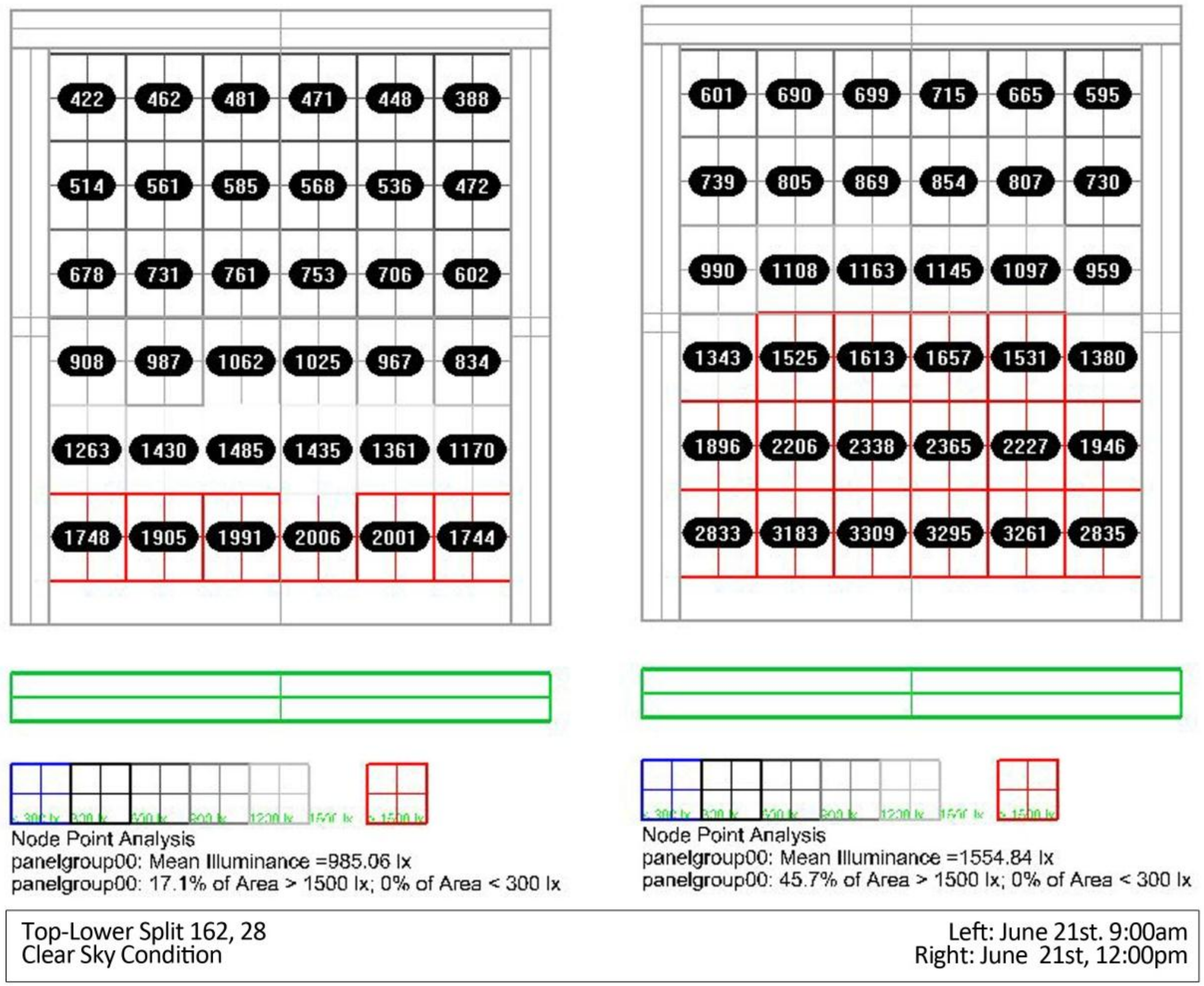


Figure 9-73: Top-lower split 162° and 28° results - The figure shows the illuminance node values inside the space.

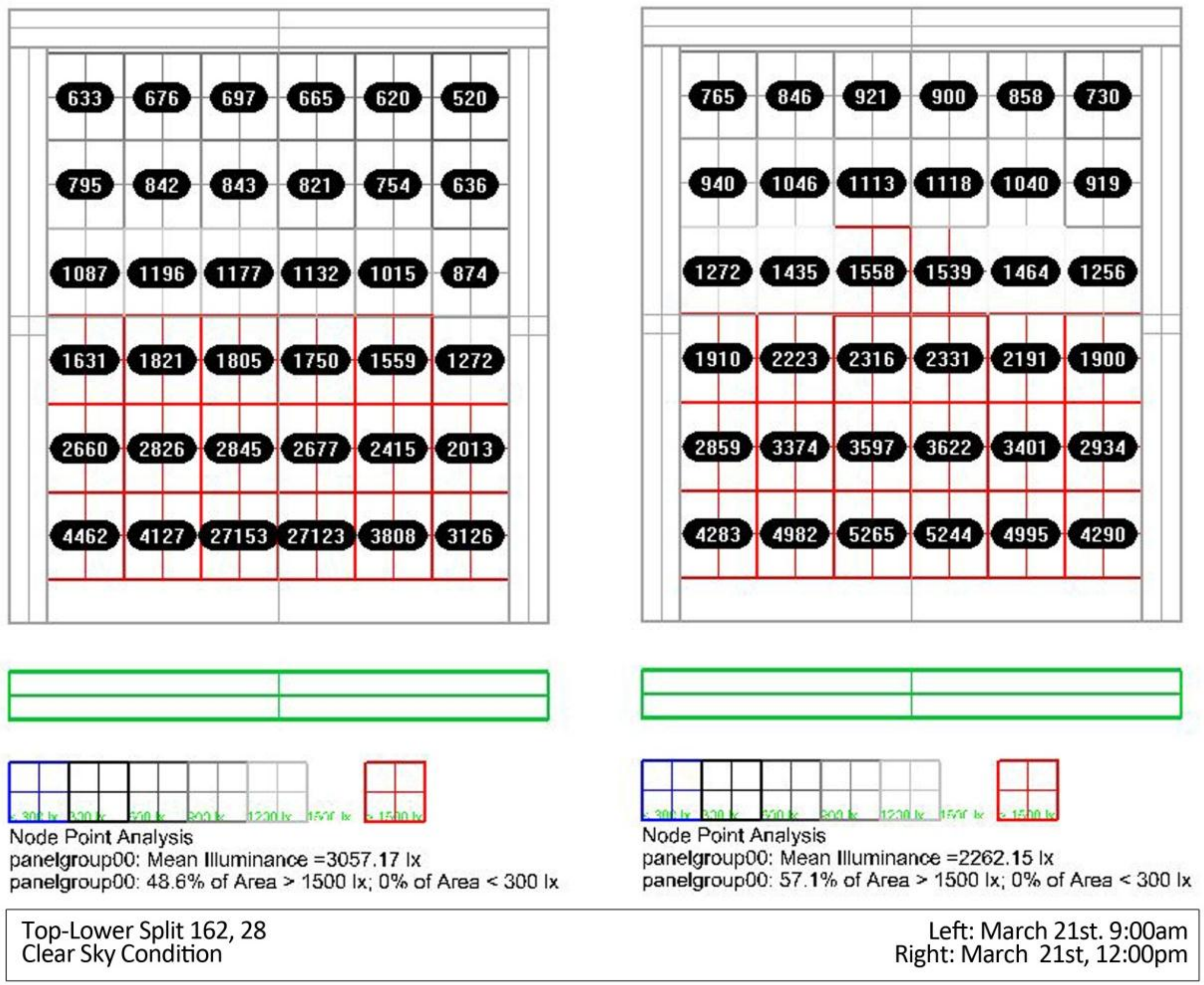


Figure 9-74: Top-lower split 162° and 28° results - The figure shows the illuminance node values inside the space.

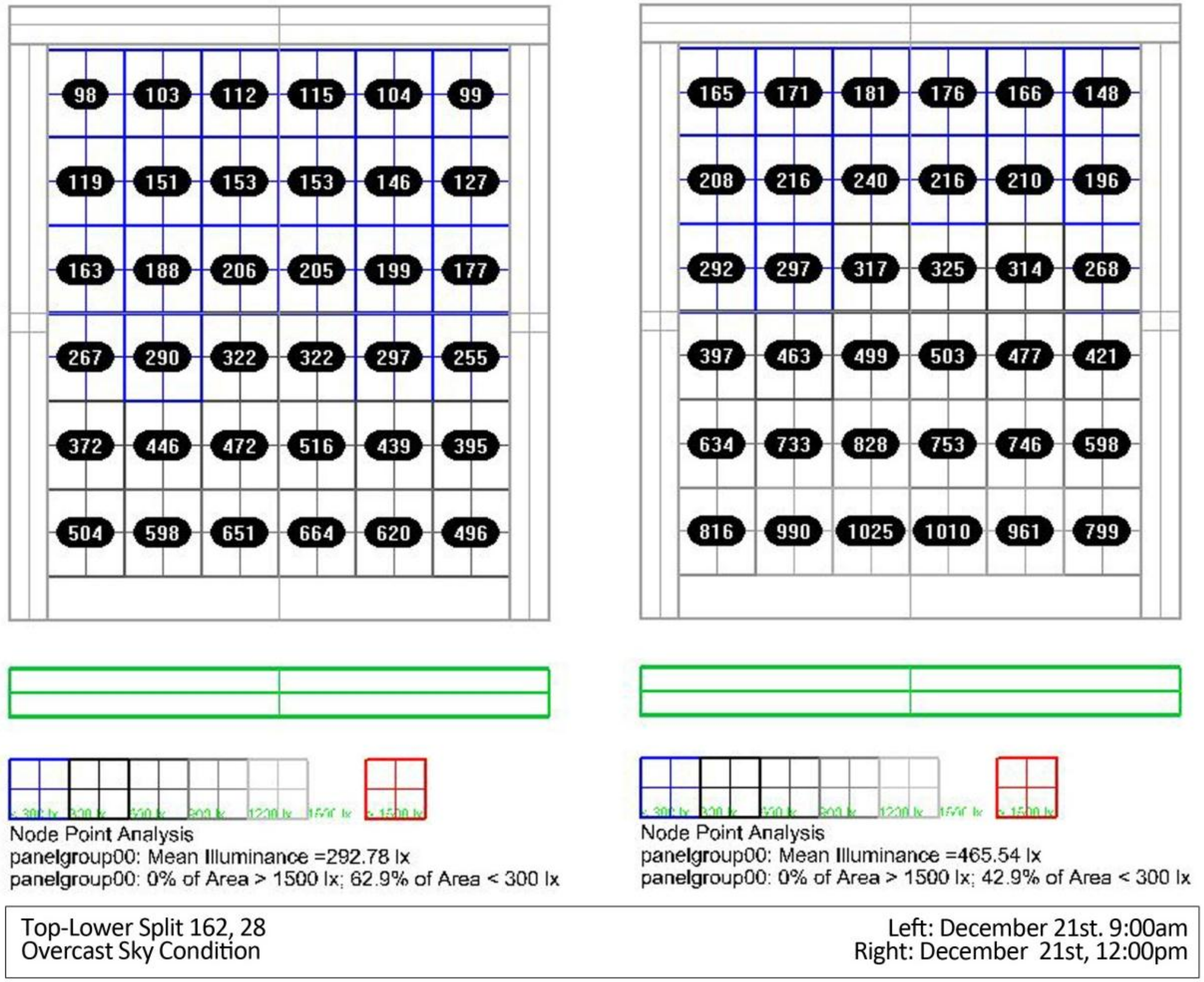


Figure 9-75: Top-lower split 162° and 28° results - The figure shows the illuminance node values inside the space.

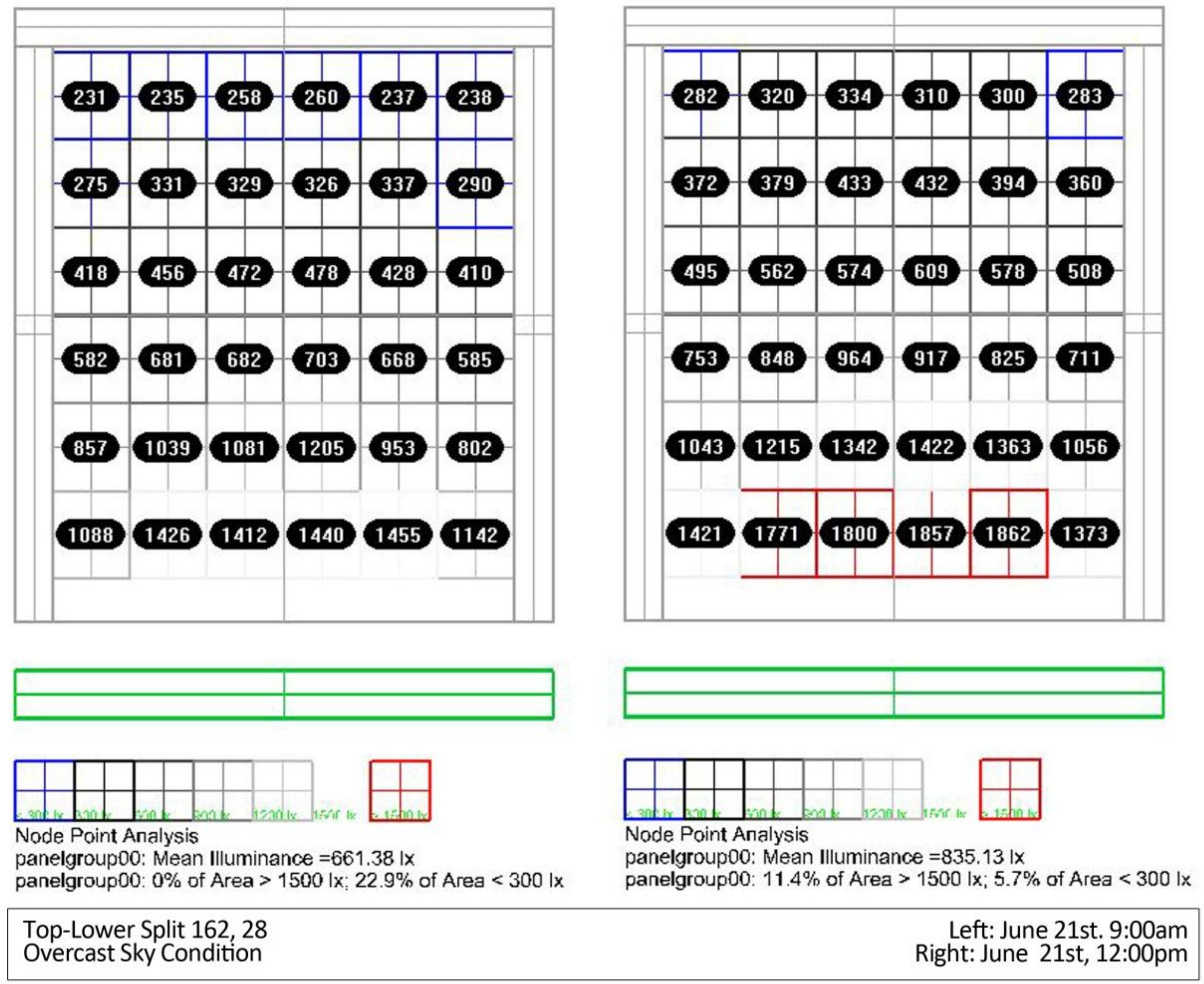


Figure 9-76: Top-lower split 162° and 28° results - The figure shows the illuminance node values inside the space.

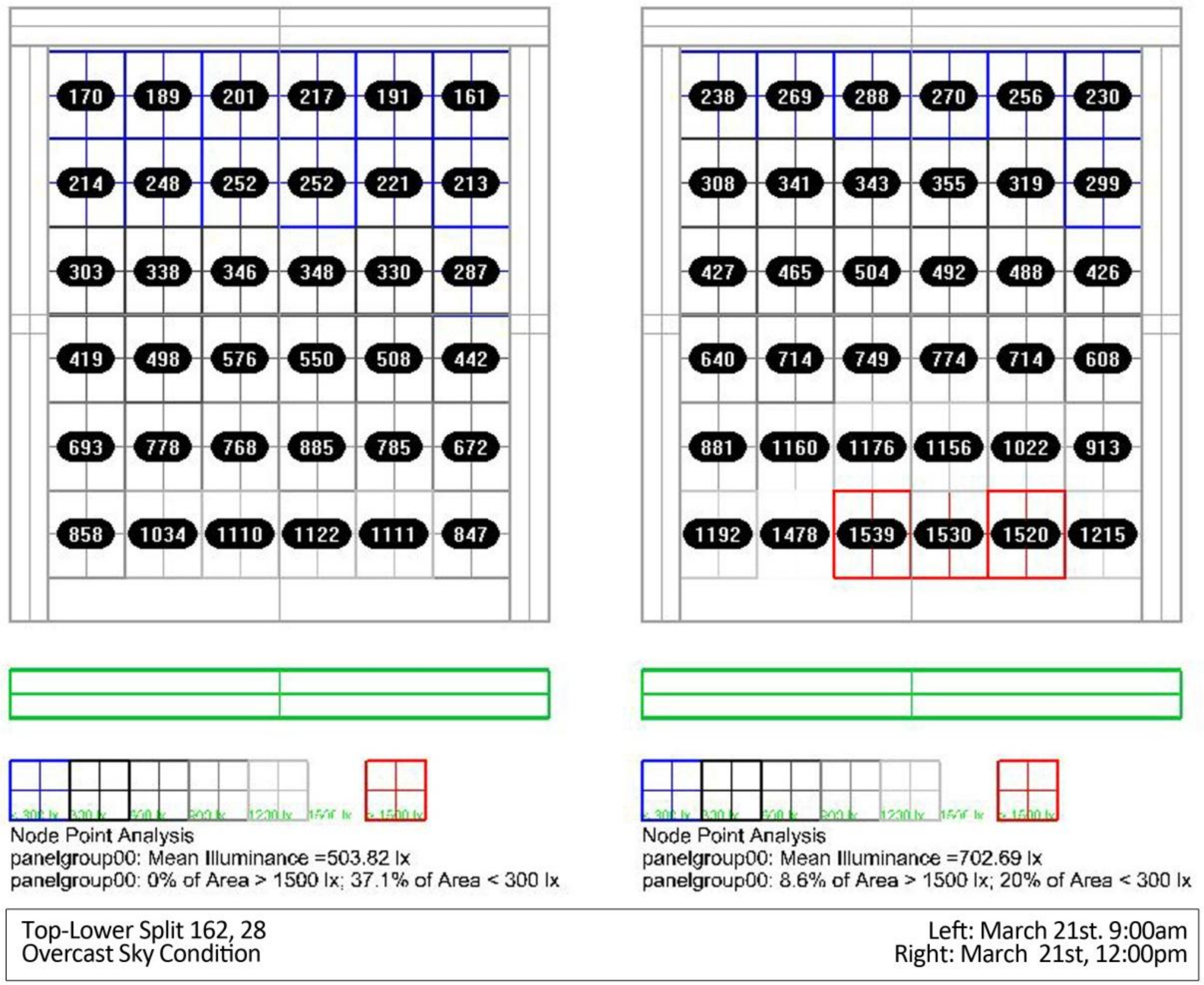


Figure 9-77: Top-lower split 162° and 28° results - The figure shows the illuminance node values inside the space.

APPENDIX B: RESULTS FOR CHART PLOTTING

	Distance from Window	Clear Sky						Overcast Sky					
		June 21st		March 21st		December 21st		June 21st		March 21st		December 21st	
		9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm
Glazing Only	0.50m	2345	3577	26772	44631	17067	30148	2729	3414	2055	2874	1212	1895
	1.50m	1584	2379	2597	3301	16455	29490	1436	1851	1116	1530	669	1036
	3.00m	1061	1569	1699	2230	15573	28656	787	987	591	847	344	558
	4.50m	729	1061	1125	1531	1914	2367	472	587	332	472	212	315
	6.00m	525	770	762	1067	1357	1773	289	373	221	320	127	206
	7.50m	435	612	586	821	1060	1417	216	279	173	239	100	149

Table 10-1: Glazing only chart values - The table shows the illuminance values, in the middle of the space, used for charts plotting.

	Distance from Window	Clear Sky						Overcast Sky					
		June 21st		March 21st		December 21st		June 21st		March 21st		December 21st	
		9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm
Lightshelf	0.50m	3130	4403	26725	44637	16624	29900	1807	2253	1375	1907	827	1322
	1.50m	2131	2971	2593	3393	16122	3615	1240	1477	898	1244	533	775
	3.00m	1383	1912	1662	2285	15379	28504	698	918	540	738	299	477
	4.50m	892	1245	1086	1498	1777	2153	425	554	310	445	186	273
	6.00m	615	850	736	1043	1241	1623	281	326	214	269	130	203
	7.50m	472	659	569	770	995	1295	210	262	167	235	96	145

Table 10-2: Lightshelf chart values - The table shows the illuminance values, in the middle of the space, used for charts plotting.

	Distance from Window	Clear Sky						Overcast Sky					
		June 21st		March 21st		December 21st		June 21st		March 21st		December 21st	
		9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm
Horizontal Louvers	0.50m	1550	2667	3751	4960	16539	5049	995	1268	751	1109	473	715
	1.50m	1115	1806	2678	3457	15958	3857	638	764	456	610	273	433
	3.00m	734	1186	1755	2334	2178	2773	400	475	272	449	155	341
	4.50m	517	834	1161	1479	1596	1956	262	346	188	297	136	203
	6.00m	391	614	746	1016	1145	1375	219	266	148	219	102	132
	7.50m	328	510	573	751	841	1034	161	223	115	181	79	127

Table 10-3: Horizontal louvers chart values - The table shows the illuminance values, in the middle of the space, used for charts plotting.

	Distance from Window	Clear Sky						Overcast Sky					
		June 21st		March 21st		December 21st		June 21st		March 21st		December 21st	
		9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm
Shading 0° and 45°	0.50m	1902	2849	3107	3853	3011	4213	1243	1560	923	1380	546	865
	1.50m	1380	2053	2227	2848	2413	3065	710	945	593	773	319	498
	3.00m	990	1450	1517	1900	1723	2053	469	610	334	490	211	335
	4.50m	693	1052	1020	1284	1253	1469	313	369	249	344	140	217
	6.00m	505	767	707	959	837	1062	217	314	179	243	105	169
	7.50m	411	627	579	743	693	877	178	213	133	193	82	117

Table 10-4: Shading 0° and 45° chart values - The table shows the illuminance values, in the middle of the space, used for charts plotting.

	Distance from Window	Clear Sky						Overcast Sky					
		June 21st		March 21st		December 21st		June 21st		March 21st		December 21st	
		9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm
Shading 10° and 45°	0.50m	1788	2868	2919	3726	2958	4269	1202	1517	883	1238	549	767
	1.50m	1301	2078	2144	2699	2248	2972	689	843	488	719	282	473
	3.00m	925	1463	1440	1852	1572	1995	423	539	314	414	192	276
	4.50m	668	1046	971	1247	1051	1304	276	362	215	286	124	195
	6.00m	505	770	680	909	739	933	185	282	157	219	85	142
	7.50m	406	609	553	691	616	787	150	194	127	174	78	123

Table 10-5: Shading 10° and 45° chart values - The table shows the illuminance values, in the middle of the space, used for charts plotting.

	Distance from Window	Clear Sky						Overcast Sky					
		June 21st		March 21st		December 21st		June 21st		March 21st		December 21st	
		9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm
Shading 35° and 55°	0.50m	1812	2664	2464	2990	2396	3167	1002	1325	803	1101	454	722
	1.50m	1343	1911	1799	2184	1706	2184	532	624	410	577	252	377
	3.00m	916	1295	1167	1503	1093	1528	307	397	234	341	144	214
	4.50m	625	862	812	1013	747	1036	212	250	159	222	92	140
	6.00m	443	619	552	680	542	661	132	168	104	150	60	96
	7.50m	329	491	452	544	439	604	101	143	82	112	47	73

Table 10-6: Shading 35° and 55° chart values - The table shows the illuminance values, in the middle of the space, used for charts plotting.

	Distance from Window	Clear Sky						Overcast Sky					
		June 21st		March 21st		December 21st		June 21st		March 21st		December 21st	
		9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm
Harvesting 145° and 160°	0.50m	1935	3325	27716	46029	17174	4497	2198	2708	1665	2240	966	1496
	1.50m	1254	2111	3461	4574	16501	29607	1443	1772	1066	1510	631	967
	3.00m	849	1454	2410	3236	15666	28887	834	1047	662	882	371	611
	4.50m	631	1026	1729	2438	2178	2554	510	669	410	530	238	378
	6.00m	453	816	1296	1821	1560	1941	346	443	272	370	156	248
	7.50m	383	654	1024	1462	1245	1603	290	354	207	299	130	212

Table 10-1: Harvesting 145° and 160° chart values - The table shows the illuminance values, in the middle of the space, used for charts plotting.

	Distance	Clear Sky						Overcast Sky					
	from	June 21st		March 21st		December 21st		June 21st		March 21st		December 21st	
	Window	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm
Harvesting 153° and 153°	0.50m	1991	3318	27791	6121	17010	4603	2153	2764	1638	2247	968	1490
	1.50m	1295	2174	3573	4656	16600	29718	1449	1792	1075	1459	657	971
	3.00m	873	1484	2498	3351	15751	28896	858	1087	649	910	367	589
	4.50m	614	1061	1810	2461	2208	2666	530	665	412	584	230	386
	6.00m	456	810	1372	1849	1548	2043	367	476	283	382	159	253
	7.50m	405	682	1098	1501	1238	1725	281	335	200	293	123	201

Table 10-7: Harvesting 153° and 153° chart values - The table shows the illuminance values, in the middle of the space, used for charts plotting.

	Distance	Clear Sky						Overcast Sky					
	from	June 21st		March 21st		December 21st		June 21st		March 21st		December 21st	
	Window	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm
Combined 24° and 156°	0.50m	1913	2835	3408	4244	16018	3968	1563	1776	1146	1544	659	1020
	1.50m	1345	1994	2481	3084	15623	3023	934	1144	785	1015	419	611
	3.00m	910	1370	1649	2116	2155	27977	653	739	440	672	267	420
	4.50m	649	974	1161	1482	1554	1809	393	512	320	430	190	316
	6.00m	484	760	819	1069	1160	1379	291	378	215	324	127	205
	7.50m	423	627	671	861	972	1201	236	292	179	247	100	160

Table 10-8: Combined 24° and 156° chart values - The table shows the illuminance values, in the middle of the space, used for charts plotting.

	Distance	Clear Sky						Overcast Sky					
	from	June 21st		March 21st		December 21st		June 21st		March 21st		December 21st	
	Window	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm
Combined 26° and 163°	0.50m	1984	2901	3372	4304	16327	1887	1397	1867	1064	1555	680	995
	1.50m	1414	2045	2480	3120	15806	1627	868	1068	674	996	422	619
	3.00m	978	1423	1643	2116	2273	1201	624	762	435	764	289	431
	4.50m	674	1017	1129	1475	1630	884	389	493	319	499	198	290
	6.00m	539	774	807	1067	1145	710	291	380	203	344	152	200
	7.50m	440	630	665	837	959	665	242	302	190	298	125	171

Table 10-9: Combined 26° and 163° chart values - The table shows the illuminance values, in the middle of the space, used for charts plotting.

	Distance	Clear Sky						Overcast Sky					
	from	June 21st		March 21st		December 21st		June 21st		March 21st		December 21st	
	Window	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm
Combined 55° and 168°	0.50m	1945	3365	3341	4144	2971	3789	1255	1569	1019	1435	620	1031
	1.50m	1475	2424	2471	3065	15271	2918	767	1024	648	907	382	647
	3.00m	982	1628	1625	2096	1772	2140	504	657	471	602	261	442
	4.50m	659	1135	1096	1408	1264	1540	363	444	302	398	177	330
	6.00m	486	805	791	999	925	1193	243	299	218	314	139	231
	7.50m	370	652	618	795	783	921	210	255	169	253	116	193

Table 10-10: Combined 55° and 168° chart values - The table shows the illuminance values, in the middle of the space, used for charts plotting.

	Distance from Window	Clear Sky						Overcast Sky					
		June 21st		March 21st		December 21st		June 21st		March 21st		December 21st	
		9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm
Combined 170° and 10°	0.50m	1785	2933	3811	4895	16801	5038	1480	1854	1087	1567	639	1028
	1.50m	1319	2087	2897	3627	3282	4018	970	1125	700	994	431	654
	3.00m	938	1473	1944	2503	15412	3016	585	762	454	645	270	437
	4.50m	681	1074	1318	1726	1812	2243	433	525	337	464	197	301
	6.00m	526	820	948	1239	1397	1656	315	391	224	320	140	213
	7.50m	464	684	742	995	1103	1350	264	309	194	272	116	182

Table 10-11: Combined 10° and 170° chart values - The table shows the illuminance values, in the middle of the space, used for charts plotting.

	Distance from Window	Clear Sky						Overcast Sky					
		June 21st		March 21st		December 21st		June 21st		March 21st		December 21st	
		9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm	9:00am	12:00pm
Combined-Split 162° and 28°	0.50m	1991	3309	27153	5265	17362	5456	1412	1800	1110	1539	651	1025
	1.50m	1485	2338	2845	3597	3637	4183	1081	1342	768	1176	472	828
	3.00m	1062	1613	1805	2316	15643	28635	682	964	576	749	322	499
	4.50m	761	1163	1177	1558	1995	2266	472	574	346	504	206	317
	6.00m	585	869	843	1113	1437	1732	329	433	252	343	153	240
	7.50m	481	699	697	921	1195	1433	258	334	201	288	112	181

Table 10-12: Top-lower split 162° and 28° chart values - The table shows the illuminance values, in the middle of the space, used for charts plotting.