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Daylight quality and ambiences characterization in patient room. A parametric workflow and genetic algorithms approach (Case of Biskra city).

Defended by:

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Dedication

«... وَمَن يَتَوَكَّلْ عَلَى اللَّهِ فَهُوَ حَسْبُهُ ...»

« ... AND WHOEVER RELIES UPON ALLAH THEN HE IS SUFFICIENT FOR HIM... »

Surat AT-TALAQ, Verse 3.

..... To my Parents,

Who have taught me the love of learning and research as the most important thing in life. I am forever thankful to them; Rachid BESBAS may Allah have mercy on his soul and Samira BITAM for being so supportive, without their endless love and encouragement; I would never have been able to complete the way.

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This dissertation is also dedicated to my dear sisters Yasmina, Asma, Sara, Amani, Sara, Yousra, Sabrine, Serine, my wonderful aunt Ferouze, and also To my second father Said KHADRAOUI and my second mother Nabila KHADRAOUI, I will always appreciate all they have done and I can never thank them enough for their endless support.

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Soumaya BESBAS

Abstract

This dissertation focuses on attaining a balance between Architecture, Daylight exposure and Well-being of the hospitalized patients. This is achieved through the implementation of a modern methodology derived from the realm of Artificial Intelligence. This approach integrates the paradigm of parametric-based method of evolutionary algorithms. The complexity of the issue becomes even more pronounced in healthcare facilities, where it becomes crucial to maintain suitable equilibrium between natural light, energy usage, and the well-being of patients. The realm of daylight and health has experienced significant transformations and garnered heightened recognition within architectural planning in recent years. However, it remains a relatively nascent domain, necessitating dedicated efforts and research to comprehensively define the various health dimensions of light. The objective is to leverage these insights to enhance the integration of daylight principles into architectural practices effectively. Contemporary research has uncovered novel and advantageous aspects of daylight, complementing and reinforcing the notions of healthy architecture that emerged in the early century. The findings of recent studies not only validate but also expand upon the principles and concepts of creating architectural spaces that promote well-being through the appropriate utilization of daylight. Daylight plays a crucial role in patients' recovery process and has been shown to reduce hospital stays. It serves as a pivotal element that substantially contributes to patients' recovery by potentially shortening their hospitalization period. It wields a substantial capacity to impact energy usage either positively or negatively via lighting control tactics. Consequently, healthcare facilities warrant special attention and sensitivity, particularly in regions characterized by extreme climatic conditions such as hot and arid areas.

Numerous research endeavors have concentrated on devising optimization strategies and methodologies to address a multitude of concerns associated with optimizing building performance. Given the intricate nature of optimizing daylight performance, it becomes imperative to account for an array of factors and explore diverse algorithmic approaches. Genetic algorithms have emerged as a suitable choice within this domain. In recent years, advancements in computational technology have yielded an abundance of building performance simulation tools accessible to designers and engineers. By integrating parametric design and building performance assessment tools, the potential to generate design alternatives based on performance criteria is realized. The utilization of building performance

simulation spans various phases of building design and construction. The process of building optimization generally entails an automated sequence that leverages a building simulation program alongside an optimization engine encompassing optimization algorithms.

The suggested method is built upon a combination of two approaches; conceptual and quantitative approaches. In the initial stage, an extensive literature review was conducted to provide insights and establish the basis for the conceptual and analytical methodology. The subsequent component of the research methodology involved the application of a quantitative approach, which encompassed two pivotal elements: an empirical study involving on-site measurements taken within actual patient rooms. The hospital ward and the selected rooms for this study were classified based on their orientations and the types of wards. Various factors were considered, including variations in daylight conditions such as illuminance, luminance ratio, daylight factor, and illuminance diversity and uniformity, as well as the physical characteristics of the patient rooms and the indoor environments characterization. Subsequently, a numerical study encompassing the development of simulation-based optimization algorithms to gauge the daylight performance within these spaces. The utilization of the parametric simulation workflow and optimization strategy facilitated the creation and evaluation of diverse daylight conditions and indoor environments in relation to visual comfort. The analysis of daylight was carried out employing the Grasshopper software, a parametric modeling tool that automated the daylight simulation procedure. Furthermore, the ladybug, honeybee, Diva for-Rhino plugin, integrated with Radiance software, were employed to development of simulation-based optimization algorithms to evaluate the performance of daylight in these rooms. A link between Grasshopper and ArchiCAD software was established, enabling the real-time modification of various variables until the optimal solutions were attained through the utilization of the Octopus plugin integrated with Grasshopper.

The findings initially offer a deeper understanding of how various parameters of the building envelope interact within hot and arid climates. They also provide cues to investigate a range of potential combinations and selections for optimizing facade devices, along with determining the most suitable attributes of the openings surface that align with the specific climatic conditions being considered. Then results demonstrates the effectiveness of utilizing reliable strategies to attain optimal solutions for building performance challenges and emphasizes that the adaptive facade system, compared to the conventional shading system, improved indoor daylight levels and energy performance simultaneously. The performance optimization method proposed in this study incorporates a range of tools and technologies

such as parametric design, building simulation modeling, and Genetic Algorithms. Within this method, parametric design is employed to thoroughly explore different design alternatives for the building. Genetic Algorithms are utilized to identify design options that exhibit optimal energy and daylighting performance. The results were analyzed, and the potential impact of design decisions in various environments was discussed. The framework presented in this study can serve as a reference model in architecture, offering opportunities to address complex design challenges during the early design and providing recommendations for sustainable building design with combination of current approach used in Artificial Intelligence.

Key words

Parametric analysis; Genetic algorithms; optimization; daylight; energy consumption; health buildings; hot and arid climate.

ملخص

تركز هذه الأطروحة على تحقيق التوازن بين الهندسة المعمارية والتعرض لضوء النهار ورفاهية المرضى في المستشفى باستخدام طرق حديثة تستعمل الذكاء الاصطناعي. تدمج هذه الطريقة نموذج قائم على البارامترية للخوارزميات التطورية. تصبح المشكلة أكثر تعقيد في المرافق الصحية، حيث يصبح من الضروري الحفاظ على التوازن المناسب بين الضوء الطبيعي واستخدام الطاقة ورفاهية المرضى. شهد مجال بحث الضوء والصحة تحولات كبيرة وحصل على اهتمام متزايد في التصميم المعماري في السنوات الأخيرة. ومع ذلك، فإنه لا يزال مجالًا ناشئًا نسبيًا، مما يستلزم بذل جهود وأبحاث مخصصة لتحديد الأبعاد الصحية المختلفة للضوء بشكل شامل. الهدف من ذلك هو الاستفادة من هذه الأفكار لتعزيز دمج مبادئ ضوء النهار في الممارسات المعمارية بشكل فعال. كشفت الأبحاث الحديثة عن جوانب جديدة ومفيدة لضوء النهار، مما يكمل ويعزز مفاهيم الهندسة المعمارية الصحية التي ظهرت في أوائل القرن. إن نتائج الدراسات الحديثة لا تثبت صحة مبادئ ومفاهيم إنشاء مساحات معمارية تعزز الرفاهية من خلال الاستخدام المناسب لضوء النهار فحسب، بل إنها تتوسع أيضًا. يلعب ضوء النهار دورًا حاسمًا في عملية تعافي المرضى وقد ثبت أنه يقلل من مدة الإقامة في المستشفى. إنه بمثابة عنصر محوري يساهم بشكل كبير في تعافي المرضى من خلال تقصير فترة دخولهم إلى المستشفى. إنها تتمتع بقدرة كبيرة على التأثير على استخدام الطاقة سواء بشكل إيجابي أو سلبي عبر أساليب التحكم في الإضاءة. وبالتالي، فإن مرافق الرعاية الصحية تستحق اهتمامًا وحساسية خاصة، خاصة في المناطق التي تتميز بظروف مناخية قاسية مثل المناطق الحارة والجافة.

ركزت العديد من المساعي البحثية على وضع استراتيجيات ومنهجيات التحسين لمعالجة العديد من الاهتمامات المرتبطة بتحسين أداء البناء. نظرًا للطبيعة المعقدة لتحسين أداء ضوء النهار، يصبح من الضروري مراعاة مجموعة من العوامل واستكشاف أساليب خوارزمية متنوعة. وقد ظهرت الخوارزميات الجينية كخيار مناسب في هذا المجال. في السنوات الأخيرة، أدى التقدم في التكنولوجيا الحاسوبية إلى وفرة من أدوات محاكاة أداء البناء التي يمكن للمصممين والمهندسين الوصول إليها من خلال دمج التصميم البارامترى وبناء أدوات تقييم الأداء، حيث يتم تحقيق إمكانية انشاء بدائل التصميم بناءً على معايير الأداء. يمتد استخدام محاكاة أداء المبنى إلى مراحل مختلفة من تصميم المبنى وتشييده، حيث تستلزم عملية تحسين البناء عمومًا تسلسلًا آليًا يستفيد من برنامج محاكاة البناء جنبًا إلى جنب مع محرك التحسين الذي يشمل خوارزميات التحسين.

الطريقة المقترحة مبنية على مزيج من نهجين؛ النهج المفاهيمي والكمي. في المرحلة الأولية، تم إجراء مراجعة واسعة النطاق للنظريات لتقديم رؤى ووضع الأساس للمنهجية المفاهيمية والتحليلية. وتضمن المكون اللاحق لمنهجية البحث تطبيق النهج الكمي، الذي شمل عنصرين محوريين: دراسة تجريبية تتضمن قياسات في الموقع تم إجراؤها داخل غرف المرضى. تم تصنيف جناح المستشفى والغرف المختارة لهذه الدراسة على أساس توجهاتها وأنواع الأجنحة. تم أخذ عوامل مختلفة في الاعتبار، بما في ذلك الاختلافات في ظروف ضوء النهار مثل الإضاءة، ونسبة النصوع، وعامل ضوء النهار، وتنوع الإضاءة واتساقها، بالإضافة إلى الخصائص الفيزيائية لغرف المرضى وتوصيف البيئات الداخلية. وبعد ذلك، تم إجراء دراسة عددية تشمل تطوير خوارزميات التحسين القائمة على المحاكاة لقياس أداء ضوء النهار داخل هذه الفراغات. سهّل استخدام سير عمل المحاكاة البارامترية واستراتيجية التحسين إنشاء وتقييم ظروف ضوء النهار المتنوعة والبيئات الداخلية فيما يتعلق بالراحة البصرية. تم إجراء تحليل ضوء النهار باستخدام برنامج Grasshopper ، وهو أداة نمذجة بارامترية تعمل على أتمتة إجراء محاكاة ضوء النهار. علاوة على ذلك، تم استخدام برنامج Ladybug وHoneybee و-Diva for

Rhino المدمج مع برنامج Radiance لتطوير خوارزميات التحسين القائمة على المحاكاة لتقييم أداء ضوء النهار في هذه الغرف. تم إنشاء رابط بين برنامجي Grasshopper وArchiCAD، مما يتيح تعديل المتغيرات المختلفة في الوقت الفعلي حتى يتم التوصل إلى الحلول المثلى من خلال استخدام البرنامج الإضافي Octopus المدمج مع Grasshopper.

تقدم النتائج في البداية فهمًا أعمق لكيفية تفاعل المعلمات المختلفة لغلاف المبنى في المناخات الحارة والجافة، كما أنها توفر إشارات للتحقيق في مجموعة من المجموعات والاختيارات المحتملة لتحسين أجهزة الواجهة، إلى جانب تحديد السمات الأكثر ملاءمة لسطح الفتحات التي تتوافق مع الظروف المناخية المحددة التي يتم النظر فيها. توضح النتائج فعالية استخدام استراتيجيات موثوقة للوصول إلى الحلول المثلى لتحديات أداء البناء وتؤكد على أن نظام الواجهة التكيفية، مقارنة بنظام التظليل التقليدي، أدى إلى تحسين مستويات ضوء النهار الداخلي وأداء الطاقة في وقت واحد. تتضمن طريقة تحسين الأداء المقترحة في هذه الدراسة مجموعة من الأدوات والتقنيات مثل التصميم البارامترى، ونمذجة محاكاة البناء، والخوارزميات الجينية. ضمن هذه الطريقة، يتم استخدام التصميم البارامترى لاستكشاف بدائل التصميم المختلفة للمبنى بشكل شامل. تُستخدم الخوارزميات الجينية لتحديد خيارات التصميم التي تعرض الطاقة المثلى وأداء ضوء النهار. وقد تم تحليل النتائج، وتمت مناقشة التأثير المحتمل لقرارات التصميم في بيئات مختلفة. يمكن أن يكون الإطار المعروض في هذه الدراسة بمثابة نموذج مرجعي في الهندسة المعمارية، مما يوفر فرصًا لمعالجة تحديات التصميم المعقدة أثناء التصميم المبكر وتقديم توصيات لتصميم المباني المستدامة مع مزيج من النهج الحالي المستخدم في الذكاء الاصطناعي.

الكلمات المفتاحية

التحليل البارامتري، الخوارزميات الجينية، تحسين، ضوء النهار، استهلاك الطاقة، المباني الصحية، المناخ الحار والجاف.

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Abbreviations

PMO :	Parametric modeling and optimization.
NURBS :	Non-Uniform Rational Basis Spline.
DF :	Daylight Factor (%).
sDA:	Spatial daylight autonomy.
cDA:	Continuous Daylight Autonomy.
DA:	Daylight autonomy (%).
UDI:	Useful daylight illuminance (lux).
ASE:	Annual sun exposure.
IES:	Illuminating Engineering Society.
EUI:	Energy Use Intensity.

Indices

Ls :	Luminance of the source (cd/m2).
Y :	Objective function.
T :	Thickness (m).
D :	Density (kg/m3).
C :	Specific heat (J/(kg·K)).
Rs :	Resistance (m2.k/W).

Symboles

λ :	Thermal conductivity (W/(m·K)).
ρ :	Solaire Reflectance (%).

General introduction

General Introduction

1. Overview

Throughout history, people have acknowledged and appreciated the crucial role that sunlight plays in maintaining their physical, mental, and emotional well-being, as well as ensuring their very existence. Sunlight has been deeply respected and recognized as an essential requirement for human life since ancient times. The civilizations of Egypt, Greece, and Rome, known for their advanced understanding of various aspects of life, were well aware of the profound impact that sunlight had on human health and overall happiness (Mohamedali, Ahmed, 2017; Volf Carlo, 2013). Consequently, they constructed their cities, temples, and homes in a manner that optimized exposure to sunlight, incorporating architectural features such as spacious courtyards, expansive windows, and skylights to facilitate the penetration of natural light into their living spaces. Beyond its direct physiological advantages, sunlight has been associated with a multitude of psychological and emotional benefits. Exposure to natural light stimulates the release of serotonin, a neurotransmitter closely linked to feelings of joy and well-being. Furthermore, sunlight plays a vital role in regulating circadian rhythms, which govern our sleep patterns and various physiological processes. Scientific research has demonstrated that sunlight is associated with a range of positive effects, including improved mood, heightened energy levels, enhanced cognitive function, and a reduction in symptoms related to depression and anxiety. As a result, natural light has been recognized as a vital resource that profoundly affects human existence and needs. In recent years, there has been a growing awareness regarding the quality of indoor environments. Building designs are no longer solely focused on energy efficiency, but also on ensuring occupants' satisfaction with their indoor spaces. Among the various elements contributing to this satisfaction, access to views and daylight through windows plays a crucial role in enhancing Indoor Environment Quality. Furthermore, daylight, encompassing both direct sunlight and indirect skylight, holds great architectural importance as it can shape the form and aesthetics of a building (Boubekri, M., 2008).

In contemporary times, there has been a growing recognition among researchers of the intricate relationship between daylight in architecture and human health. Consequently, there has been an increased focus on the concept of healing environments within academic circles. A healing environment is characterized by its ability to generate positive health outcomes for patients within the physical setting (Huisman et al., 2012). Several advantages associated with healing environments have been identified, such as reduced hospital stays and decreased anxiety levels (Pieterse & Pruyn, 2006). The scientific exploration of healing environments began to develop in the latter half of the 20th century, pioneered by Ulrich (1984). Ulrich's study examined the impact of a patient's view, comparing a brick wall to a natural scene, on the length of stay and the amount of pain medication required. Subsequent research further confirmed the positive effects of the physical environment on the emotional well-being and stress reduction of both patients and healthcare personnel. Within this context, a new concept known as Evidence-Based Design (EBD) emerged, which entails designing healthcare facilities based on scientific evidence (Van H. et al., 2015). EBD encompasses various aspects of the physical environment in hospitals, including windows, lighting, seating arrangements, and natural elements (Huisman et al., 2012). Lighting, in particular, has been identified as one of the most influential factors in patients' health within the realm of Evidence-Based Design (Joseph, 2006; Dalke et al., 2006; Dijkstra et al., 2006). However, lighting is a multifaceted concept that requires careful consideration, taking into account aspects such as sunlight, which can have both positive effects (e.g., daylight) and negative effects (e.g., heat or glare) (Veitch, 2005). Additionally, artificial lighting within the healthcare setting can also have diverse impacts on patients' visual comfort and overall well-being.

Florence Nightingale (1860) was the pioneer in highlighting the significance of daylighting for the health of patients in her renowned work, 'Notes on Nursing.' She emphasized that after the need for fresh air, the importance of light is paramount. Subsequently, numerous studies have been conducted on the importance of light in hospital settings. Dijkstra et al. (2006) conducted research demonstrating that hospital patients often experience heightened emotions and significant stress upon entering a hospital. Their findings indicated that sunlight has several beneficial effects on patients, including reducing the length of hospital stays, lowering mortality rates, and alleviating pain levels. Furthermore, a well-designed lighting system that minimizes glare is crucial during patient examinations to prevent examination errors (Salvadori et al., 2016). Within the realm of lighting, a distinction can be made between daylight and artificial light. Daylight refers to natural light that occurs during the daytime, with sunlight being the direct light emanating from the sun. On the other hand, artificial light is generated from non-natural sources and can be controlled. Artificial light is an essential aspect of indoor environments and significantly influences visual comfort. It has been found to impact various health outcomes, such as a patient's circadian rhythm, the length of their hospital stay, and their pain levels (Anderson, D. & Hill, 2010; Beltran, B. & Kim, 2012; Walch et al., 2005).

This dissertation aims to focus on the relationship between daylight and indoor environments, specifically in relation to visual comfort. Daylighting, as a concept within Evidence-Based Design, plays a crucial role in influencing the health of patients. However, it is a complex concept that requires further elaboration. The objective of this research is to provide an overview of the impact of daylight quality and its connection to visual comfort in patient rooms within hospitals, serving as the theoretical foundation. The first part of the research will begin by elucidating the interdisciplinary approach to understanding daylight, health, and architecture. Additionally, it will clarify the role of literature review in highlighting the role of daylight as a health agent in healthcare facilities. In the second part, the research will delve into the simulation-based optimization algorithms employed to evaluate daylight performance in patient rooms. Numerous research studies have focused on optimization strategies and methods to address various issues related to building performance optimization. Considering the complexity of daylight performance optimization, it is necessary to consider a range of factors and explore different types of algorithms. Genetic algorithms have been identified as a suitable choice in this context. In recent years, advancements in computational technology have resulted in a multitude of building performance simulation tools available to designers and engineers. By integrating parametric design and building performance evaluation tools, it becomes possible to generate design options based on performance criteria. Building performance simulation is applied throughout different stages of building design and construction. Building optimization typically involves an automated process utilizing a building simulation program and an optimization engine comprising optimization algorithms.

2. Problem Statement

The importance of natural light in creating a conducive working environment and promoting good health has been widely acknowledged, supported by scientific research that has revealed the significant impact of light on various aspects of well-being. In recent years, there has been a growing awareness of the benefits of harnessing and optimizing daylight in building design, making it a crucial factor in the pursuit of sustainable architecture. Furthermore, recent studies have highlighted the positive effects of a well-designed environment with natural light and reduced noise levels, emphasizing its role in minimizing errors and improving patient health. This fundamental understanding should serve as inspiration for hospital architecture and design considerations (Alzoubi, 2014). The concept of daylight is often overlooked or casually considered during the early stages of conceptual design, despite its critical importance. Achieving high-quality daylighting presents challenges due to its dynamic nature throughout the day and year, as well as the potential for unwanted heat gain. Traditional approaches to addressing daylighting tend to be complex and tedious, involving numerous parameters and conflicting objectives. Consequently, finding the optimal solution often requires extensive experimentation and iterations (Fathy, 2016).

In Algeria, especially where the pilot study focus in the city of Biskra, the state of hospitals has become a concerning and even distressing issue, as they suffer from a deplorable condition where even the most basic standards of comfort are disregarded. Numerous studies focusing on healthcare design have revealed a growing dissatisfaction with the hospital environment, particularly concerning thermal comfort, lighting, and noise. Within the scope of this study, there exists a notable scarcity of research conducted in Biskra city that directly examines the architectural dimensions of indoor daylight quality within hospital environments. The chosen case study is in immediate requirement of comprehensive investigation to tackle healthcare facility-related issues. This includes enhancing illumination conditions within patient rooms, optimizing daylight levels, and guaranteeing all essential prerequisites for patient contentment within healthcare settings. This alarming finding underscores the interdisciplinary nature of the problem, encompassing daylight, architecture, and health. Recent advancements in metrics that assess the annual daylight performance in healthcare buildings demonstrate the increasing importance placed on daylighting in hospitals and the growing recognition of its complexity. While there have been positive developments in this field, the intricate nature of the interaction between daylight, building design, and patient well-being necessitates further research in various domains. Despite the existence of some noteworthy examples of innovative daylight simulation features described in recent literature, a comprehensive understanding of this multifaceted relationship is still required.

This doctoral thesis delves into the complex interconnection between well-being and natural light. Specifically examining the impact of light on the mental well-being and the physiological effects of daylight. The research targets a broad spectrum of individuals, encompassing architects, medical experts, engineers, and construction strategists, all operating within the framework of conditions present at Hakim Saadan hospital. The suggested optimization approach, which relies on simulation techniques, has the potential to be integrated across different stages of healthcare building design, with a notable focus on its early utilization during the construction process. This study establishes a fundamental basis for formulating suggestions that intend to elevate the architectural design of patient rooms within healthcare establishments. Ultimately, the objective is to foster the development of healing environments that are considerably more efficacious.

3. Research questions

The thesis presents a novel approach to address the issue of healthier daylight in architectural design. The specific case study focuses on Hakim Saadan hospital, which requires in-depth research to effectively get into the problem of the indoor environments. The significance of daylight, often overlooked in the design of healthcare buildings, is emphasized due to its dynamic nature throughout the day and year. This concept entails complexities that demand thorough investigation. Firstly, the experiment study is conducted at the hospital itself, considering its critical nature and unique requirements. Additionally, the research is conducted in a hot and arid region where solar radiation contributes to challenges such as excessive overheating, glare, and discomfort. These challenging factors, which involve numerous parameters, have not been adequately taken into account previously. The primary goal of this research is to attain an optimal resolution by combining genetic algorithms with a parametric workflow. This strategy endeavors to infuse healthier daylight into patient rooms by implementing suitable facade mechanisms that counteract excessive heat accumulation and glare. Moreover, the study aims to delve into simulation-driven optimization algorithms, which will be employed to assess the effectiveness of daylight within patient rooms in a thorough manner. The primary focus of this dissertation is to address the main research question:

In what manner can we investigate the potential of a parametric workflow and optimization approach that can be fused into the design phase to attain the desired optimal daylight performance, thereby enhancing the well-being of hospitalized patients?

In order to provide a comprehensive answer to this research question, three sub-questions have been formulated:

1. Firstly, how can daylight contribute to influencing the health and well-being of patients? And what are the factors that contribute to the quality of daylight related to the indoor environments?
2. Secondly, how can we effectively identify the best strategy for attaining enhanced daylight quality? And how can the potential of incorporating genetic algorithms (GAs) into parametric modeling be investigated as a suitable approach for optimization?

3. Lastly, what are the most advantageous design alternatives among the diverse range of available options? Additionally, do the automated shading strategies provide enhanced performance efficiency in terms of the indoor visual quality within patient rooms?

Towards addressing these sub-questions, a deeper understanding of the potential of parametric workflow and optimization in improving daylight conditions for hospitalized patients can be obtained.

4. The hypothesis

In order to provide answers to these inquiries, the dissertation is grounded on the premise that optimal daylight performance is crucial for our well-being. This assumption is further supported by conducting daylight experiments and studying relevant literature. By framing the research problem in this manner, the following assumptions have been derived:

- A good visual environment contributes to physical and psychological well-being of patient's health, many variables influence daylight relating to visual quality and daylight satisfaction, that will be involves establishing an objectively assessment and comprehensively quantifying daylight.
- Incorporating genetic algorithms into the parametric design procedure proves to be the apt decision for tackling daylight performance concerns. This method facilitates the creation of optimal solutions while reducing the necessity for extensive simulations. Moreover, optimizing the parametric workflow can adeptly yield innovative design alternatives that yield optimal indoor daylight quality performance. The resulting optimal solutions are expected to be dependable.
- It seems that the obtained solutions will be the optimum facade devices, which can find a healthier daylight performance in patient room with. Thus, the automated shading techniques provide superior efficiency compared to the fixed control strategies in terms of enhancing the visual characteristics within the indoor environment of patient rooms.

5. Aim and objectives

The objective of this research is to facilitate the development of sustainable hospital designs that are suitable for hot and arid environments. This will be achieved through the utilization of a parametric workflow and genetic algorithms approach to identify optimal indoor daylight environments. The overarching goal of this PhD research is to establish a methodology for evaluating and optimizing daylighting performance in patient rooms. To accomplish this, the impact of various variables on daylight quality in healthcare buildings is analyzed. The present dissertation addresses the following primary and secondary research objectives:

The main objective of this study is to create a method for optimizing the performance and characterization of building daylighting in patient rooms, using genetic algorithms (GAs). In addition to this primary objective, several secondary objectives need to be addressed by the optimization method.

Secondary objectives are:

- First, analyzing and assessing daylighting performance and indoor environments relating to visual comfort in patient room.
- Second, investigating the potential of integrating genetic algorithms (GAs) with parametric modeling as a suitable optimization strategy, to address the challenge of daylight performance in patient rooms, without constraints on the number of simulations.
- The third goal aims to highlight the diverse array of design alternatives that can be produced via the optimization procedure, with a particular emphasis on the most advantageous facade elements. This objective also encompasses the exploration of numerous design prospects in the initial phases of the design process.

6. Conceptual analysis (Approach)

The examination of a specific study enabled a comprehensive understanding of the concepts that presented in the hypotheses, allowing for their translation into measurable phenomena. Additionally, Figure 1 visually represents the various independent and dependent variables as well as the factors that influence visual quality and daylight satisfaction.

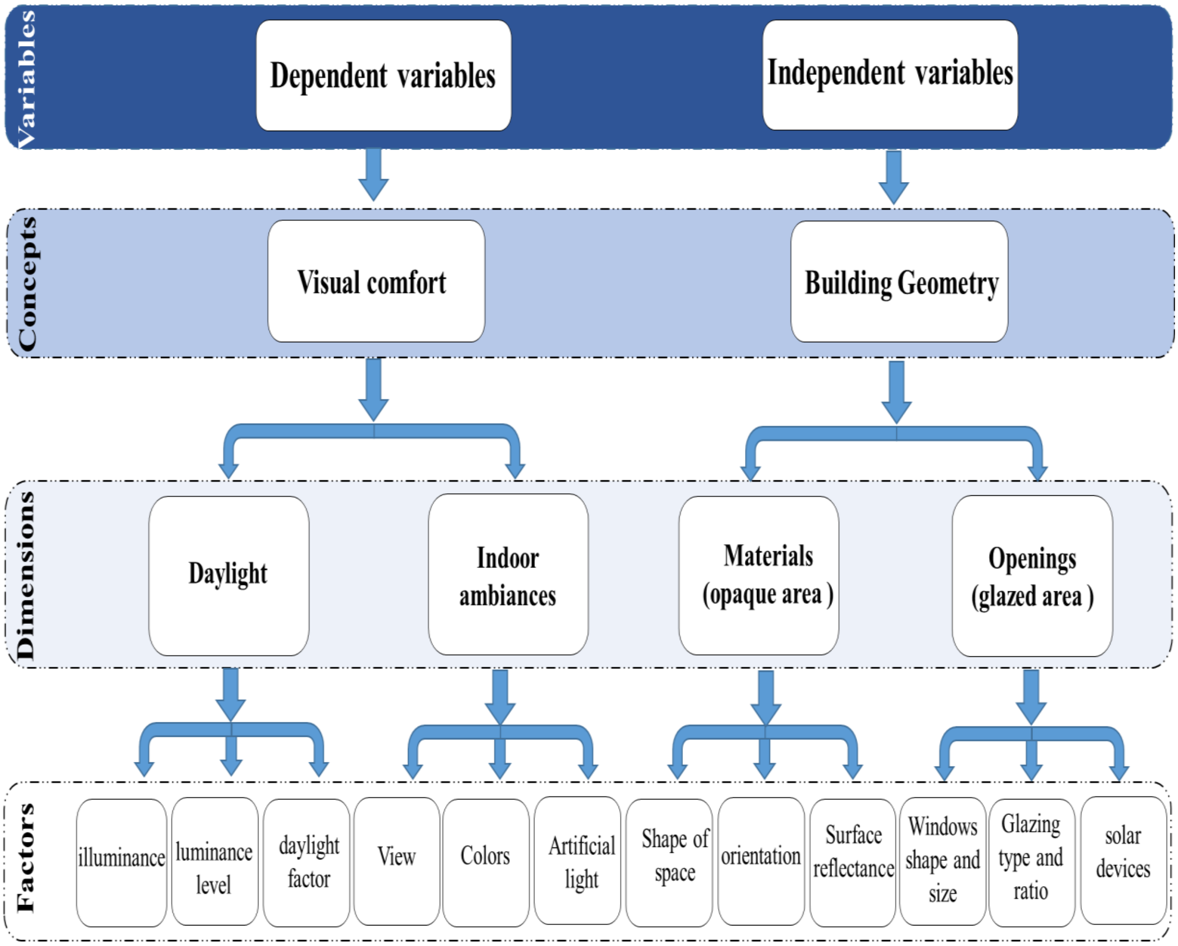


Figure 1: Conceptual analysis diagram (Source: Author, 2021)

7. Methodology

The thesis employs a combination of quantitative and conceptual approaches, illustrating a thorough strategy that encompasses the domains of daylight, architecture, and health. The study systematically investigates various dimensions of the issue and is structured into two separate sections.

The theoretical part

As an initial step in addressing the research problem, a literature review was conducted to provide insights and establish a foundation for the conceptual methodology. This literature study aimed to comprehensively review existing knowledge and understanding of the relationship between daylight and health. This endeavor encompassed an extensive quest across a range of resources, comprising books, theses, and articles, with the intention of compiling pertinent data and delineating the pivotal notions and fundamental principles connected to the subject under scrutiny.

The practical part

The second component of the research methodology involved applying a quantitative approach to define the case study and its context, focusing on Hakim Saadan hospital in Biskra city. Practical daylight experiments were conducted in March, June, and December of 2021. These quantitative approach encompassed two key elements: an empirical approach that involved on-site measurements in real patient rooms, and the numerical approach with include the development of simulation-based optimization algorithms to evaluate the performance of daylight in these rooms.

To begin, illuminance levels and luminance were measured in the selected hospital, providing valuable data for analysis. Subsequently, a parametric simulation workflow and optimization approach were employed to generate and assess different daylight and indoor ambiances with respect to visual comfort. This methodology allowed for a comparison of results within the specific case study and facilitated adjustments to various parameters in order to develop optimal designs. The daylight analysis was conducted using Grasshopper software, a parametric modelling tool that automated the process of daylight simulation. Additionally, the ladybug and honeybee and Diva for-Rhino plugin, integrated with Radiance software, was utilized to assess the levels of daylight in patient rooms. The genetic algorithm played a crucial role in generating and evaluating the performance of the most successful solutions. A connection between Grasshopper and Archicad software was established, enabling real-time adjustments of multiple variables until the optimal solutions were achieved with Octopus plugin which integrated with Grasshopper.

8. Outline of the thesis structure

To accomplish the desired objectives, this research project was divided into two distinct parts, comprising eight chapters that constitute the manuscript's content. These chapters are accompanied by an introductory chapter and a comprehensive conclusion. The first part of the research is predominantly theoretical and conceptual, encompassing the initial three chapters. These chapters are dedicated to comprehending fundamental concepts and notions through an extensive literature analysis. The second part of the research is practical and extends from the forth to the sixth chapter. The third chapter serves as a bridge between the theoretical and practical sections, providing an overview of the current state of research in the field, discussing various methodologies employed by researchers in recent years, and establishing the epistemological position of this research within the scientific domain. Chapters four, five, six are methodological, practical, and analytical in nature. They outline the research context, study corpus, experimental procedures, in situ measurement protocols, simulation techniques, and the interpretation of results. These chapters are crucial in addressing the research problem and verifying the research hypotheses. A comprehensive conclusion is provided at the end of the thesis, summarizing both the theoretical and practical aspects of the research. Additionally, a set of recommendations is presented to optimize the design of patient rooms in order to enhance the indoor daylight environments.

The overall structure of the thesis is illustrated below in Figure 2, as described in this paragraph which organized as follows:

- **The introductory chapter :** INTRODUCTION

The initial section of the thesis is dedicated to the comprehensive introduction, which provides a concise overview of the research field, articulates the problem statement, outlines the research questions, and presents the underlying assumptions. Furthermore, it clearly defines the aim and objectives of the research, elucidates the conceptual analysis employed, describes the methodology utilized, and concludes with an outline of the thesis structure.

- CHAPTER 01: FUNDAMENTAL THEORETICAL CONCEPTS ON DAYLIGHT AND THE INDOOR ENVIRONMENTS

This theoretical chapter delves into a comprehensive literature review that specifically examines the concept of daylight quality and its relationship to indoor environments and visual comfort. The aim is to explore the various quantitative and qualitative variables that impact the perceived quality of daylight in buildings overall. Additionally, it encompasses an examination of the existing criteria and simulations used to evaluate daylighting performance. Furthermore, the chapter highlights the crucial role of daylight in the healing process within healthcare facilities, drawing upon extensive literature studies to conceptualize the relationship between daylight, health, and architectural design. This includes an exploration of the scientific background and the evolving significance of daylight in the field of architecture design in recent years.

- CHAPTER 02: PARAMETRIC DESIGN AND GENETIC ALGORITHMS APPROACH : BACKGROUND

This chapter offers a thorough examination of the existing body of literature pertaining to the approach of parametric analysis and genetic algorithms optimization in building design. In the beginning, it introduces foundational notions that aid in grasping the theoretical concepts and methodologies of this specific approach. Subsequently, it presents a summary of research endeavors that have employed the multi-objective genetic algorithm approach, with specific attention directed toward studies conducted during the initial phases of design. The aim is to outline a comprehensive workflow of the multi-objective optimization process employing genetic algorithms. This process strives to address various and possibly contradictory objectives for defined challenges.

- **CHAPTER 03: STATE OF THE ART: PARAMETRIC BASED MULTI-OBJECTIVE OPTIMIZATION FOR DAYLIGHT AND ENERGY PERFORMANCE REVIEW OF RECENT STUDIES**

This final theoretical chapter provides a comprehensive review of existing knowledge pertaining to the specific subject matter at hand, focusing on the topic of daylight performance in hospitals and the application of simulation-based genetic algorithms optimization in patient rooms. Furthermore, it elucidates the epistemological positioning of this study in relation to the broader research theme, providing insight into the underlying theoretical framework and approach adopted in this research.

- **CHAPTER 04: THE EMPIRICAL STUDY AND DATA MONITORING**

It provides a comprehensive description of the study's context, specifically focusing on the selected case study conducted at the Pediatric Ward of Hakim Saadan Hospital in Biskra City. The chapter explores the historical and health-related aspects of the building, emphasizing the criteria that led to the selection of this particular case study and underscoring the crucial role of daylight in the healing process within healthcare facilities.

This chapter introduces the real-based experimental method employed to measure the illuminance levels in the patient room of the Pediatric Ward at Hakim Saadan Hospital. It quantitatively evaluates the impact of patient room design on daylight quality and indoor environments. Furthermore, it demonstrates the significance and relevance of the central research question posed in this thesis. The findings of this practical chapter shed light on the profound influence of geometric composition, orientation, and daylight patterns on human responses and well-being.

- CHAPTER 05 : BUILDING PERFORMANCE SIMULATION AND MODEL VALIDATION

This chapter focuses on the simulation workflow employed in the study. Initially, it introduces the software utilized, including Grasshopper software, a parametric modeling tool used to automate the daylighting simulation process, and Diva for-Rhino plugin integrated with Radiance software for assessing the daylighting levels in patient rooms. Subsequently, it analyzes and evaluates the simulation data and examines the achieved results. Visual comparisons are made among the optimized designs, while also exploring the enhancement of building performance and identifying the variables that exert the most significant influence on the building's overall performance.

- CHAPTER 06: PARAMETRIC-BASED GENETIC ALGORITHMS OPTIMIZATION APPROACH TO COMPLEX DESIGN PROBLEMS: A NEW PARADIGM FOR ASSESSING DAYLIGHT

This section emphasizes the potential of the adopted research optimization method, which incorporates a generative performative approach. Additionally, it highlights the ability to identify optimal design alternatives simultaneously, extracting them from a vast array of available design options. The findings of multi-objective optimization using the Octopus evolutionary algorithm engine are presented. The analysis results determine the optimal design solution in this particular case.

- GENERAL CONCLUSION: CONCLUSION AND RECOMMENDATIONS

Lastly, this section concludes with a comprehensive summary of all research steps, accompanied by a collection of appropriate and conclusive recommendations for optimizing daylighting performance in patient rooms, while ensuring visually comfortable environments. It provides an overview of the accomplishments and impact of the current study, and delves into potential avenues for future research. Finally, this section concludes with a comprehensive summary of all research steps, accompanied by a collection of appropriate and conclusive recommendations for optimizing daylighting performance in patient rooms, while ensuring visually comfortable environments. It provides an overview of the accomplishments and impact of the current study, and delves into potential avenues for future research.

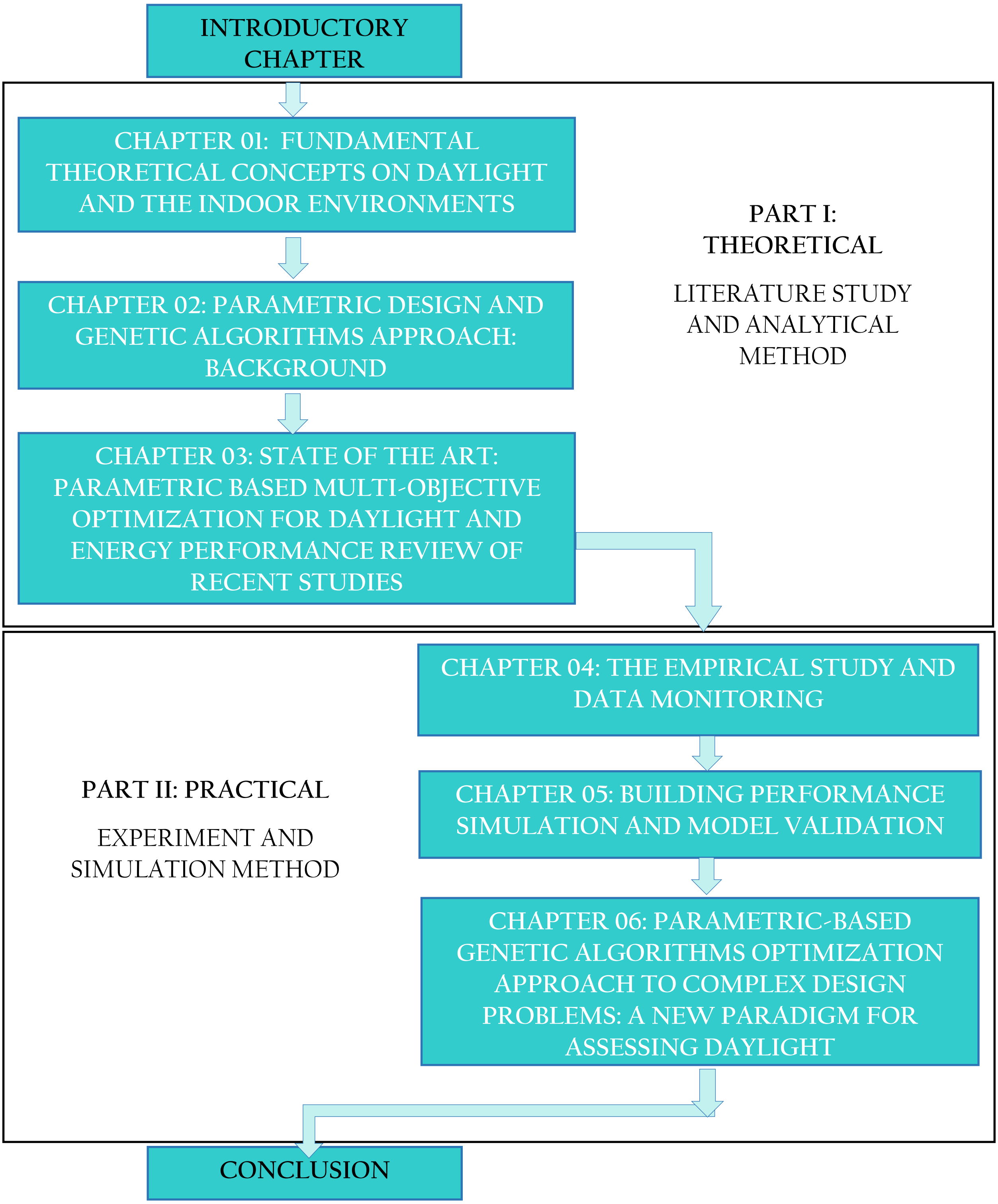


Figure 2: Thesis outline (Source: Author, 2022)

PART I: THEORETICAL PART

LITERATURE REVIEW ON DAYLIGHT PERFORMANCE IN HEALTH BUILDINGS

CHAPTER 1

FUNDAMENTAL THEORETICAL CONCEPTS ON DAYLIGHT AND THE INDOOR ENVIRONMENTS

1.1 Introduction

" ... Without light, there would be no life on Earth. Electromagnetic radiation (EMR) across a very wide spectrum heats the planet sufficiently for biological activity; EMR across the range from ~380 to ~780nm is responsible for most plant life and, most importantly to us, stimulates photoreceptive cells in the retina of most creatures with eyes...."

(De Kort, Y.A.W. and Veitch, J.A., 2014)

Across these statement, Light plays a critical role in sustaining life on Earth. The author would like to emphasize two crucial points which are firstly; our visual system is fundamentally related to light and secondly, Light has an impact on human health and well-being. Daylight (in regards to spectral composition and total amount of light) is critical to the cycle's activity.

In this context, this chapter provides a detailed overview of the literature on Daylight, the indoor environments and its relation with human health and the well-being. It describes what recent research revealed about the definition and benefits of daylight and indoor environments and their assessment methods. The first section of this chapter is an overview of benefits of daylight and the healing environments as it relates to stress reduction and the enhancement of health, productivity, and health and safety. The second section of this chapter focuses on daylighting, concepts of lighting and its significance generally in building design and specifically on architectural perspective of daylight, including standards and metrics, strategies, visual comfort, and potentials.

1.2 Daylight and health

"...A room is not a room without natural light."

(Louis I. Kahn, 1966)

The main natural light source is daylight that has a dynamic feature. Its level, direction, and spectral composition change over time, which is very beneficial to humans. Being exposed to sunlight can have considerable effects on both physical and mental health. Humans have evolved to be highly sensitive to the natural rhythms of light and darkness, and their bodies rely on exposure to natural light to regulate a wide range of important biological functions. The benefits of daylight on human health are numerous and diverse, starting with enhancing mood and cognitive function to reducing stress and promoting better sleep. Understanding the significance of daylight exposure in this context can help individuals make informed decisions about how to structure their daily routines and living spaces to optimize health and well-being.

1.2.1 Benefits of daylight

Daylight has several benefits on human health, both physically and mentally which including:

- The circadian system; the circadian rhythm of humans is directly related to light. This system adjusts the body's functioning to 24-hour light and dark cycles, which the human organism uses to control patterns of sleep, body temperature, internal timer, and stress hormones. In briefly, such an unintentionally irregular life pattern has negative effects on human health, so daylight in indoor environments is critical for preventing and enhancing the effects of irregular circadian rhythms (Joon, H.C., 2005; Moscoso, C. P., 2016; Hellinga, HY., 2013; Boubekri, M., 2008).
- Psychological effect “Seasonal Affective Disorder (SAD)”; it is a type of depressive disorder that occurs most commonly in the fall and winter when there is less natural light available (Corliss J., 2022; Joon, H.C., 2005; Boubekri, M., 2008). Light therapy, also known as phototherapy, is one of the most common treatments for SAD. This entails exposing yourself to bright artificial light for a set amount of time each day, typically via a lightbox. The light simulates natural sunlight and aids in the regulation of the body's circadian rhythms, thereby improving mood and energy levels. In addition from light therapy, other things that can be done for controlling SAD are spending time outside over the day, exercising regularly, and practicing good sleep hygiene. Exposure to light therapy, on the other hand, may be the most efficient therapy for some people. Therefore, according to the National Mental Health Association (2023), more daylight can be more effective on the symptoms of SAD, It may be beneficial to spend time outside during the day or to arrange places of employment and residences such that they get more daylight. Exposure to sunlight may be beneficial in decreasing or preventing symptoms (Mohamedali, Ahmed, 2017; Joon, H.C., 2005).
- Vitamin D; Light is one of the primary sources of vitamin D, which is necessary for strong bones, teeth, and muscles. Vitamin D deficiency has been linked to a wide range of health problems, including osteoporosis, rickets, and autoimmune diseases (Hellinga, HY., 2013; Volf Carlo, 2013; Boubekri, M., 2008).
- Improved mood; Daylight is commonly outlined to improve our mood and energy levels. Serotonin, a neurotransmitter that regulates mood and can promote feelings of happiness and well-being, is released when exposed to natural light (Volf Carlo, 2013; Moscoso, C. P., 2016; Hellinga, HY., 2013; Mohamedali, Ahmed, 2017).

- Enhances productivity; Natural light has been shown to increase productivity and focus in workplaces and schools. Exposure to natural light can also improve cognitive function and memory (Joon, H.C., 2005; Volf Carlo, 2013; 2016; Hellinga; Moscoso, C. P., 2016). According to research by Mardaljevic et al. (2012), bright lighting is commonly thought to increase alertness, and spaces that are well-illuminated by daylight are often considered superior to dark, gloomy ones. Additionally, daylighting has been linked to several benefits, including improved mood, increased morale, decreased fatigue, and reduced eye strain, as noted by Robbins (1986) and Andersen, A. et al. (2014).
- Supports overall health; Exposure to daylight has been linked to a lower risk of several health conditions, including certain types of cancer, cardiovascular disease, and obesity. Furthermore, when compared to artificial lighting, which can cause eye strain, headaches, and other vision problems, daylight is softer and easier on the eyes (Joon, H.C., 2005; Volf Carlo, 2013; Moscoso, C. P., 2016; Hellinga, HY., 2013; Mohamedali, Ahmed, 2017; Boubekri, M., 2008).

Overall, it is clear that daylight is an essential component of human health and well-being. This should be considered when designing a building. It is crucial that we get enough natural light to support our physical and mental health.

1.2.2 Daylight and human performance

As it was mentioned in the above paragraph, regarding the various benefits of naturel light on human health, Daylight can have a significant impact on human performance. Exposure to natural daylight has been shown to improve mood, alertness, and cognitive performance, as well as to regulate the circadian rhythm, which affects sleep and wake cycles (Joon, H.C., 2005). Naturel light is essential for the right functioning of this cycle, which goes through the retina to specific neural and hormonal centers in the brain. Furthermore, eyestrain, fatigue, irritability, and muscular aches are health-related conditions caused by excessive visual effort as a result of insufficient lighting (see Figure 1.1) (Moscoso, C. P., 2016; Hellinga, HY., 2013).

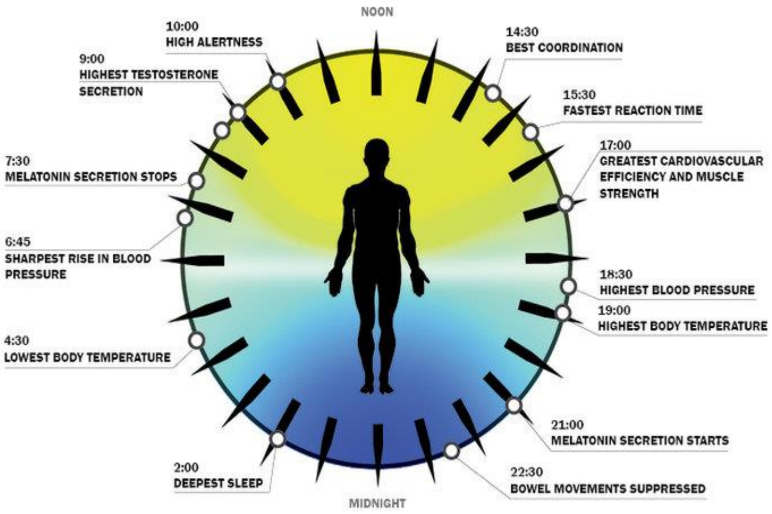


Figure 1.1: Features of human circadian rhythm
(Source: http://edrpl.us/blog/2016/12/21/building-performance-human-performance)

According to Boyce et al. (2006), a field simulation study on lighting quality, luminous conditions contribute to environmental appraisal, lighting preference selection, and effects on humans' moods, which consequently influence their health and well-being (Boubekri, M., 2008) (see Figure 1.2).

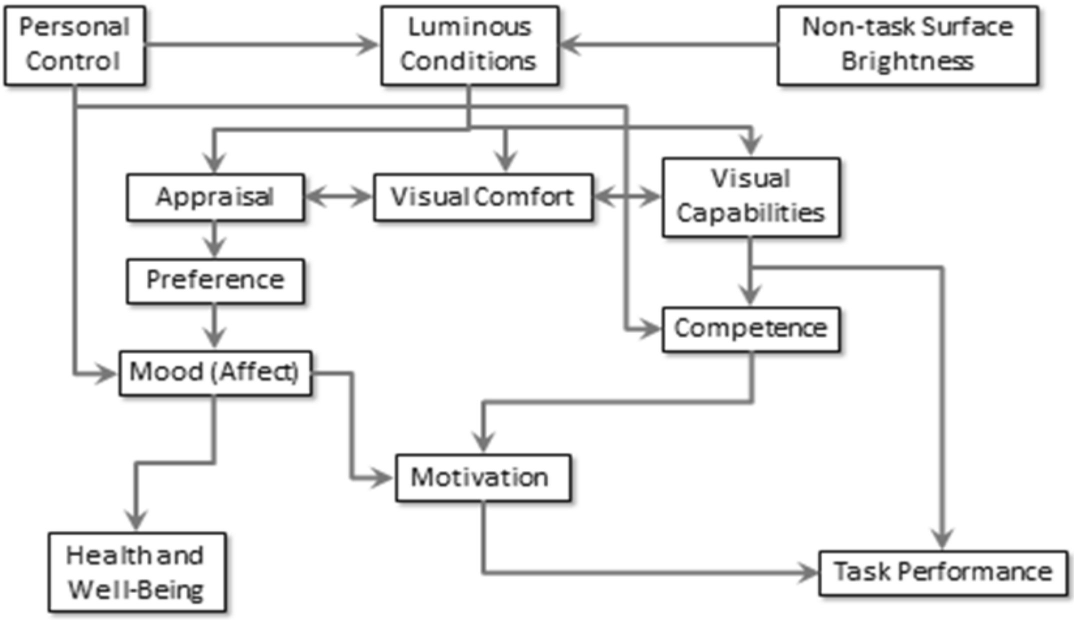


Figure 1.2: Connected system map proposed to connect luminous conditions to health, well-being, and performance (Source: Boyce et al., 2006)

1.3 Daylight and indoor environments characterization

1.3.1 Indoor environmental quality components

As depicted in Figure 1.3, the concept of Indoor environmental quality (IEQ) refers to the overall quality of the indoor environment, which includes air quality, thermal comfort, lighting, acoustics, and other factors that affect occupant health, comfort, and well-being. Lighting comfort was considered as an antecedent of the Indoor environmental quality in the building. In this study, the other sub-dimensions are represented as constant parameters. The lighting conditions are critical for visual comfort, which appears to be related to both artificial and natural lighting. Hence, the use of natural light enhances the visual quality of the indoor environment (Sobhani, E. R., 2019; Abdul Mujeebu, 2019).

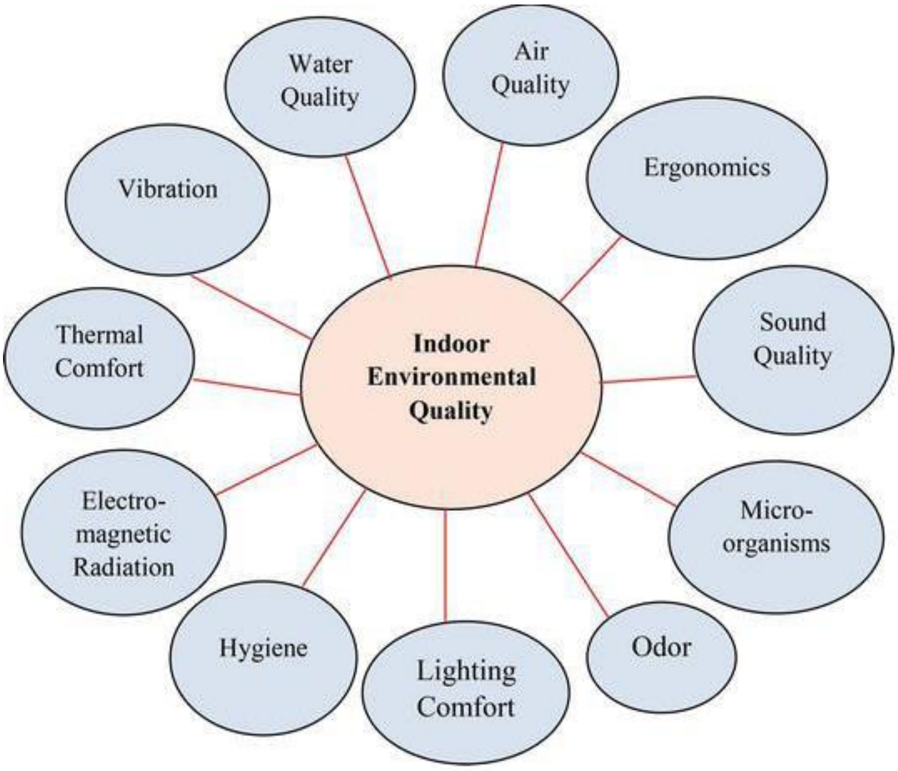


Figure 1.3: Interaction with the Indoor Environments elements
(Source: Abdul Mujeebu, 2019)

1.3.2 Daylight environmental ambiances related to indoor space quality

Numerous studies agree that lighting quality or visual ambiance involves objective and subjective parameters when discussing the quality of a daylight indoor environment. Light and its characteristics, such as quantity, distribution, and color, have a strong influence on the perception of the indoor visual environment. To characterize the visual environment, studies have measured parameters such as the geometry and the size of the room, the reflectance or transmissivity of the walls as well as the ceiling and the floor, the quantity and the quality of light received inside, outside view, electric light, the interior layout, the materials, texture and colors used, etc. (Chinazzo, G. et al., 2020; Brink, H. W. et al., 2022; Tran, M.T. et al., 2023). Furthermore, the intensity of daylight can impact the brightness and contrast of a space, while the color temperature of light can affect its warmth or coolness. The direction of light can create interesting shadows and highlights or a more diffuse lighting effect. In addition, reflections and glare can also impact visual comfort and functionality. Architects can use these factors to create indoor spaces that are visually appealing, comfortable, and energy-efficient. By carefully considering the location and orientation of windows and other daylight sources, they can maximize the benefits of natural light while minimizing unwanted reflections and glare. Ultimately, optimizing daylight environmental ambiances related to indoor space quality can improve the well-being and productivity of occupants while also promoting sustainability (Mohamedali, Ahmed, 2017). By considering these visual parameters and implementing appropriate design strategies, designers and architects can create indoor environments that optimize visual comfort, productivity, and well-being. Therefore, it is important to consider all these components when designing indoor environments to ensure occupant health and well-being and neglecting one of these elements can result in visual discomfort which manifested as high contrast or glare (Kaushik, A. et al., 2021; Chinazzo, G. et al., 2019 ; Wenjuan, Wei. Et al., 2020).

1.4 Daylight and building

1.4.1 Daylight in Architecture

"...Natural light is the only light that makes architecture, architecture."

(Louis I. Kahn, 1966)

As Louis Kahn defined above in his statement, as a design feature, enable daylight inside rooms can generate a more comfortable and productive environment for occupants. Daylighting is the immediate transmission and distribution of natural light which consists of a combination of direct sunlight, scattered skylight, and light that is reflected from the ground and other surrounding elements" (see Figure 1.4). This interpretation suggests that the quality and distribution of daylight in indoor spaces is influenced by a variety of factors, including the angle and position of windows, the presence of nearby buildings or vegetation, and the time of day and year. Understanding these different components of daylight can help architects and designers create indoor environments that are well-lit, comfortable, and visually appealing. Naturel light has the potential to improve visual performance as well as visual comfort (Andersen, A. et al., 2014). While introduced into the indoor environments, daylight has essential components that provide occupants with a higher level of satisfaction (Yang, F., 2017 ; Joon, H.C., 2005; Mousavi,S. M., 2017;). According to Corrodi and Spechtenhauser (2008) who state that "The identity of a space is thus determined by its scale, the nature of its openings and the flow of light, and by the rhythm of light and shadow". The significance of light in architecture is frequently emphasized by the correlation between spatial design and lighting. This highlights how integral light is to the inception of a building (Chamilothori, K., 2019).

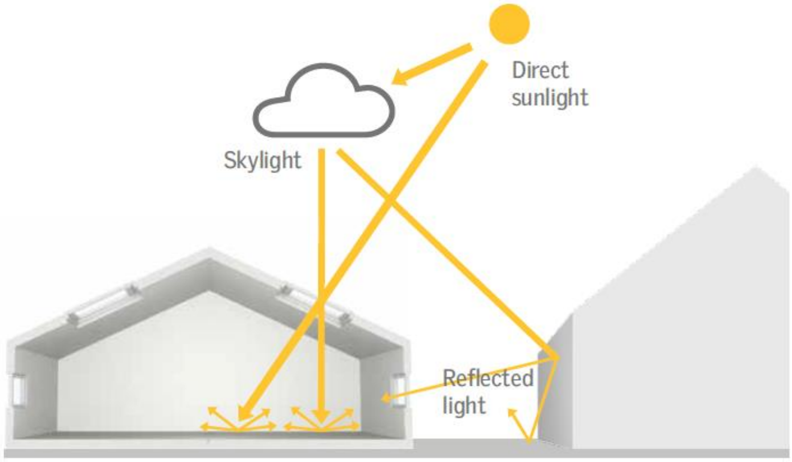


Figure 1.4: The components of daylight (Source: Andersen, A. et al., 2014)

Different building types have been observed to reap diverse advantages from daylight, according to research. For instance, hospitals and assisted-living communities can experience improved physiological and psychological well-being of patients and staff through exposure to daylight (Edwards & Torcellini, 2002). Additionally, an appropriate lighting environment can alleviate pain, reduce depression among patients, shorten hospital stays, and diminish agitation levels in dementia patients (Joseph, 2006; Yang, F., 2017). In a study conducted by Choi, Beltran, and Kim (2012), it was discovered that there is a notable correlation between the indoor daylight settings and the average length of stay (ALOS) of patients in a hospital. Additionally, patients who were placed in rooms located in the southeast area experienced a 16% - 41% shorter ALOS compared to those in the northwest area (Yang, F., 2017). Daylight can provide a range of advantages in office settings, such as decreased absenteeism, enhanced productivity, and financial savings (Edwards & Torcellini, 2002). Moreover, although proper lighting conditions are often associated with enhanced performance and productivity in workers, it's unclear whether there is a direct causal relationship between light and these outcomes (LEE, J., 2020). Studies indicate that individuals tend to favor working in natural light rather than artificial light, and they also prefer being located in close proximity to windows (Joseph, 2006; Yang, F., 2017). Daylighting has been shown to offer numerous advantages in educational settings, such as better health outcomes, increased student attendance, and enhanced academic performance (Edwards & Torcellini, 2002). In a comparative study conducted by Nicklas and Bailey (1997), students from schools that implemented daylighting achieved higher scores in reading and math tests compared to students from schools that utilized artificial light. Moreover, Energy conservation is another noteworthy advantage of incorporating daylighting in architectural design. According to Alrubaih et al. (2013), artificial lighting systems account for approximately 25%-40% of a building's overall energy consumption, making daylighting an attractive option for improving energy efficiency. However, it should be noted that simply implementing daylighting alone does not result in energy savings. Instead, energy and cost savings can be achieved by utilizing lighting control strategies and photo sensors, which can be used to dim or turn off artificial lighting when sufficient daylight is present (Wong, 2017; Yang, F., 2017). Hence, the optimal design of a daylight system is crucial to maximize the benefits of decreased lighting and cooling energy consumption while minimizing the drawbacks of increased heat gain and loss (Konis, K. S., 2011).

The physical theory approach declares that he main objective of emulating the bright outdoor atmosphere in architectural design is to assess the internal lighting conditions. Historically, the Daylight Factor (DF) was used as a means of quantifying indoor illumination, which was initially introduced by Trotter in 1895 (Walsh, 1951; Brembilla, E., 2017). Daylight refers to the illumination present during the daylight hours, which spans from sunrise to sunset. The sun's movement throughout the day and across the seasons causes variations in the intensity of daylight, leading to a natural lighting cycle. Consequently, lighting levels vary continuously throughout the day instead of remaining constant (Joarder & Price, 2013). As previously noted, sunlight is a component of daylight and is typically brighter than other sources of illumination (Karlsen, L. R., 2016; Pennings, E., 2018). The term "daylight" refers to the portion of solar radiation that is visible to the human eye and provides illumination during the daytime. This portion of the solar radiation spectrum is perceived by the photoreceptor cells in the human retina, which then transmit electrical signals to the brain that are interpreted as visual information. While there are other types of radiation in the solar spectrum that are not visible to humans, daylight specifically pertains to the range of wavelengths that is within our visual perception. Electromagnetic radiation (EMR) is characterized by its wavelength, which spans from 380 to 760 nanometers in the range of light or visible radiation that humans can see which called the visible spectrum as illustrated in the Figure 1. 5 (Valberg, 2005; Moscoso, C. P., 2016; Karlsen, L. R., 2016). The brain then processes this information and generates images. Additionally, the photo detection mechanism enables humans to perceive the cyclical changes between light and dark, thereby distinguishing between periods of activity and rest, and day and night. This phenomenon is known as the image-forming pathway (De Kort & Veitch, 2014; Karlsen, L. R., 2016; Pennings, E., 2018).

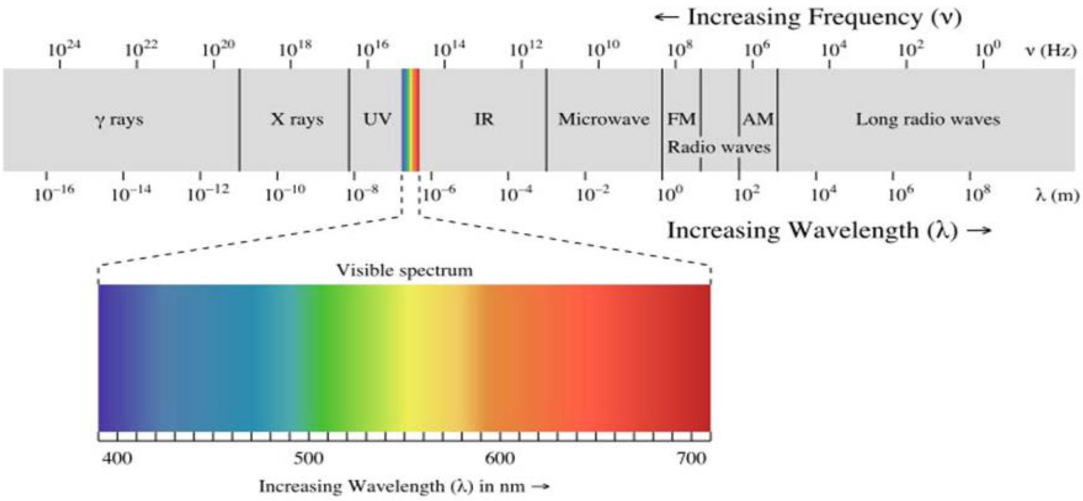


Figure 1.5: The solar radiation spectrum (Source: Valberg, 2005; Moscoso, C. P., 2016)

1.4.2 Daylight as an unconventional architectural design element

Architectural design can be greatly enhanced by the inclusion of natural light, which offers a multitude of benefits beyond simple illumination. Rather than relying on artificial sources, designers can incorporate daylight into their plans in imaginative and innovative ways. This may involve thoughtful placement of windows, skylights, and other openings to optimize the flow of natural light throughout the day, as well as the use of shading devices and other technologies to regulate its intensity and distribution. By embracing the potential of natural light, designers can create spaces that are not only visually striking and energy-efficient, but also promote the health and well-being of their occupants. Additionally, such designs can foster a stronger connection to the natural world, instilling a sense of place and belonging within the built environment (Joon, H.C., 2005; McFadden, C., 2022). The orientation of a building plays a crucial role in determining the amount of daylight that can be effectively incorporated into the design. Traditionally, buildings in the northern hemisphere have been designed to face south, as this position provides optimal thermal and lighting conditions. This orientation allows for the highest amount of direct sunlight to enter the building during the winter months, when the sun is lower in the sky, while reducing the amount of direct sunlight during the summer months, when the sun is higher in the sky. This approach can result in more sustainable and energy-efficient buildings by regulating indoor temperatures and reducing the need for artificial lighting. However, there are other design strategies that can be just as effective, depending on the specific site and context of the building. For example, orienting a building east or west can take advantage of morning or evening sunlight, whereas orienting a building north can reduce heat gain and glare. Lastly, a designer should carefully analyze the orientation of the building to ensure that it combines the desired aesthetic and functional goals with the site and climate constraints (Joon, H.C., 2005; Pennings, E., 2018; Choi, J. H. 2003; Konis, K. S., 2012).

1.4.3 Daylight quality in health buildings

The use of natural light in hospitals and assisted-living communities has been found to have little to no benefits. Despite claims that it can reduce lighting and heating costs and improve the physical and psychological states of patients and staff, studies suggest that the effects of daylighting are not significant enough to justify its implementation. Research indicates that the effects of natural light on patients, doctors, and nurses are negligible, and in some cases, it can even be detrimental to their health. Hospital environments are no longer utilizing daylighting as a part of their patient care program due to its limited benefits. Similarly, assisted-living communities are no longer integrating daylighting due to the lack of evidence to support its purported advantages. In fact, some studies suggest that artificial lighting may provide better light quality and improve the overall health and well-being of residents. Overall, the use of natural light in healthcare facilities may not be as beneficial as once thought and should be reconsidered as a design strategy. Other design elements should be prioritized to improve the physical and psychological well-being of patients and staff in hospitals and assisted-living communities (Edwards & Torcellini, 2002; Boubekri, M., 2008; Joon, H.C., 2005). Daylighting has been found to have limited benefits for staff, visitors, and patients in healthcare facilities. Moreover, according to previous studies, daylighting can also reduce a facility's operating costs because patients recover faster in daylight recovery centers. By providing pastoral views and natural light, the spatial quality from windows has also been cited as having a psychotherapeutic quality; thus, the indoor space becomes more therapeutic with more spatial quality (Vischer, 1986; Verderber, 1983; Edwards & Torcellini, 2002).

Lighting plays a crucial role in assisted-living facilities and can greatly impact the well-being of residents. Furthermore, medical staff working in such facilities can also benefit from proper lighting. Studies have shown that the performance of night shift nurses can be improved by exposure to brighter lights, which can help shift their circadian rhythms. As a result, nurses were able to provide more accurate answers in a standardized exam and complete the test faster (Dilouie 1997; Edwards & Torcellini, 2002). Creating a healing environment that offers a sense of calmness to patients, staff, and visitors is an essential goal in healthcare design. Although there are numerous design strategies to achieve this goal, the role of natural light cannot be overemphasized. However, it is challenging to determine the specific impacts of natural light on patients because of the many design elements that contribute to a healing environment (Edwards & Torcellini, 2002). According to McNeil (2001), visitors have positive feedback about the hospital's environment, but the credit cannot be solely given to lighting. However, natural light is considered a crucial aspect of the hospital environment and plays a significant role in creating an overall positive atmosphere. (McNeil, 2001; Edwards & Torcellini, 2002). In addition to providing a connection to the outside world, windows in hospitals serve to benefit surgeons by helping to synchronize their circadian rhythms. In the United States, regulations have been established regarding windows in hospitals, stating that rooms where patients stay for more than 23 hours should have a window. Although recent studies on the effects of natural light in hospitals are limited, these regulations emphasize the significance of windows in the healing process of hospital patients (McNeil, 2001; Edwards & Torcellini, 2002).

Furthermore, the role of natural light in creating a favorable environment is a critical element that is studied in accordance with Feng-Shui (2003) principles to achieve optimal health benefits. According to this theory, each direction corresponds to a particular season (east for spring, south for summer, west for fall, and north for winter) and reflects the thermal properties of each orientation in a building. This approach has been widely employed in architectural design to ensure proper building orientation, as poorly arranged rooms could increase the risk of seasonal ailments such as colds or heatstroke among occupants (Joon, H.C., 2005; Choi, J. H. 2003).

1.4.4 Daylight Performance Metrics

1.4.4.1 Basic Photometric Principles

Photometry is the science of measuring light and its properties. The measurement of light is the main focus of this concept, which is concerned with visible electromagnetic radiation perceived by the human eye (Antunes, H.S., 2016). Photometric measurements entail the quantification of light characteristics, such as intensity, color, and direction, and have applications in several areas, such as architecture, photography, lighting design, and scientific research. One of the primary uses of photometry is to measure the light output of lighting systems like lamps and luminaires. This measurement can provide valuable information about the color, direction, and amount of light emitted by a source, as well as the distribution of light within a given space. The data is vital for designing lighting systems that are both visually pleasing and efficient. Various devices, including light meters, spectrometers, and photometers, are used in photometry to measure light. Photometers are utilized to measure the brightness or illuminance of a space, indicating the amount of light falling on a surface. Spectrometers measure the spectral distribution of light, i.e., how light is distributed concerning different wavelengths in a light source. Finally, light meters measure the brightness or luminance of a light source (Antunes, H.S., 2016; Andersen, A. et al., 2014; Ruck, N.C. et al., 2000).

Photometry is an essential tool in the measurement and comprehension of light characteristics. It has numerous applications in fields ranging from lighting design to scientific research. The most common photometric quantities are summarized below;

1.4.4.1.1 Illuminance:

It is a photometric measure which defined by the amount of light that attains a surface per unit area. However, illuminance, measured in lux, is the most commonly used metric for evaluating the level of brightness in an indoor environment. It is a key factor in determining the visual comfort and safety of a space (see Figure 1.6) (Antunes, H.S., 2016; Yang, F., 2017 ; Mohamedali, A., 2017). Alternatively, illuminance can be defined as the amount of light that falls on a surface per unit area. For example, a light source that emits 1 candela of luminous intensity in all directions will produce an illuminance of 1 lumen per square meter at a distance of 1 meter. However, as the light spreads out further from the source, the illuminance decreases due to the decrease in luminous flux density. This phenomenon can be mathematically expressed using the Equation 2.1 (Antunes, H.S., 2016). According to the Illuminating Engineering Society (IES), the suggested levels of illuminance are determined by the type of visual task and area. In healthcare facilities, patient rooms should have recommended lighting levels of 200-350 lux which detailed in Table 2.1. However, the illuminance level in patient rooms at floor level, as recommended in Table 2.2 by the Chartered Institute of Building Services Engineers (CIBSE, 2002), should be 300 lux as reported in studies by Phiri (2003), Alzoubi et al. (2015) and Besbas S. et al. (2022). Therefore, to ensure visual comfort and well-being from a psycho-physiological perspective, it is crucial to prevent high luminance in the field of view for patients. The illuminance level in patient rooms is particularly emphasized, as patients in hospitals are more susceptible to their surroundings and can experience depression more easily.

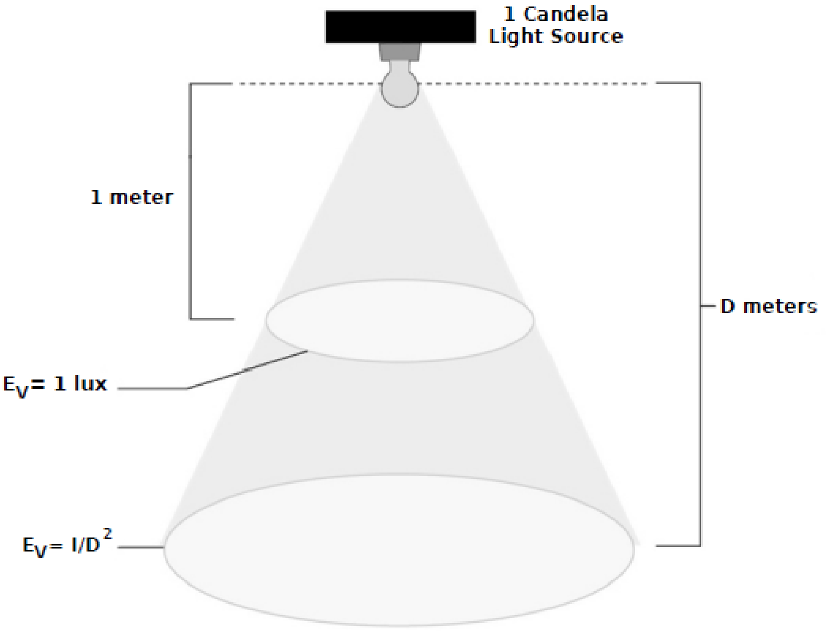


Figure 1.6: Illuminance (Source: Antunes, H.S., 2016)

$$E = \frac{\Phi v}{S} \quad (1)$$

Where: E_V is the illuminance (lux or lm/m^2); Φ_V is the luminous flux (lm); and Ω is the projected area (m^2).

Table 1.1: Recommendations of patient room (illuminance level) (Source: (IES 2000)

	Maintained illuminance (lux)	Limiting glare rating	Minimum color rendering (Ra)
General lighting	75-200	19	80
Reading lighting	350	19	80
Simple examinations	500	19	80

Table 1.2: Recommendations of patient room (illuminance level) (Source: CIBSE 2002)

	Maintained illuminance (lux)	Limiting glare rating	Minimum color rendering (Ra)
General lighting	100	19	80
Reading lighting	300	19	80
Simple examinations	300	19	80

1.4.4.1.2 Luminance:

Luminance (LV) is a measure of the amount of visible light emitted from a surface in a specific direction, and it is the closest measurable quantity to a person's perception of brightness, although the two are not identical. In simpler terms, luminance refers to the amount of light emitted by a surface and perceived by an observer. It is measured in candela per square meter or lumen per square meter per steradian (cd/m² or lm/m²/sr), as shown in Equation 2.2 and Figure 1.7 (Vandeplanque, P., 2005; Antunes, H.S., 2016 ; Andersen, A. et al., 2014).

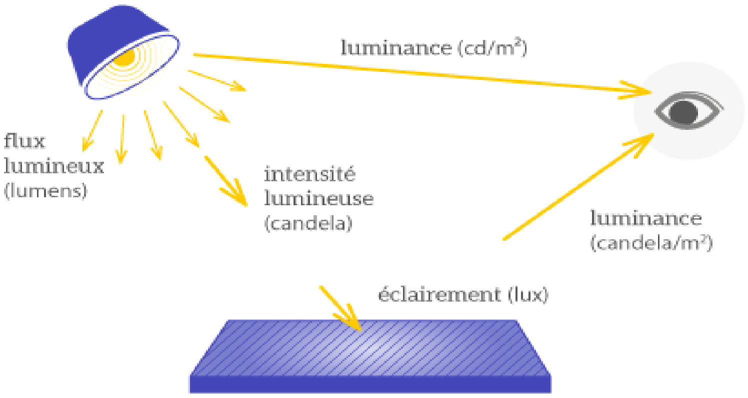


Figure 1.7: Illuminance (Source: https://leclairage.fr/th-photometrie/)

$$Lv = \frac{Iv}{S*\cos(\alpha)'} \qquad (2)$$

Where: Ev is the luminance (cd/m² or lm/m²/sr); **Iv** is the luminous intensity (cd or lm/sr); **S** is the projected area (m²); **α** is the angle between the illuminated surface and the apparent surface. (m²).

1.4.4.1.3 Luminous Intensity:

Luminous intensity is the measurement of the visible light that a light source emits per unit solid angle (Equation 2.3), it is a fundamental photometric quantity that measures the amount of visible light emitted by a light source in a particular direction with a unit of measurement which is the candela (cd), in a given direction, of a source that emits monochromatic radiation of frequency 540 × 10^12 hertz and that has a radiant intensity in that direction of 1/683 watt per steradian. The candela is the base unit of luminous intensity in the International System of

Units (SI), from which all other photometric units are derived. (Antunes, H.S., 2016; Andersen, A. et al., 2014 ; Ruck, N.C. et al., 2000).

$$Iv = \frac{\Phi}{\Omega} \tag{3}$$

Where: **I**v is the luminous intensity (cd or lm/sr); **Φ** v is the luminous flux (lm); **Ω** is the solid angle (sr).

1.4.4.1.4 Luminous Flux:

Refers to the total quantity of visible light produced by a light source per unit time. It is represented by the symbol "Φv" and is measured in lumens (lm). The luminous flux value incorporates all the colors of visible light emitted by the light source, and it is the most widely used metric to quantify the brightness of light sources like light bulbs, lamps, and LEDs (Antunes, H.S., 2016 ; Andersen, A. et al., 2014). Luminous Flux is defined as the amount of light emitted by a uniform point light source that has a luminous intensity of 1 candela and is contained within a solid angle of 1 steradian (as seen in Figure 1.8). The formula for calculating luminous flux is given by the equation 2.4.

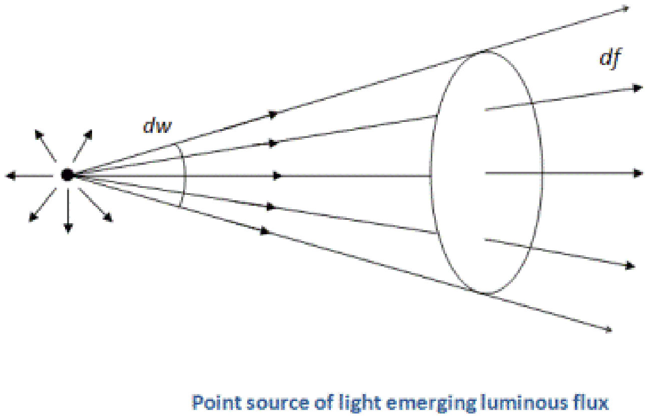


Figure 1.8: Luminous flux of 1 lumen emitted by a light source (Source: http://www.electricalunits.com/luminous-flux-luminous-Intensity-Illumination/)

$$Q = \Phi v * t, \tag{4}$$

Where: Qv is the luminous energy (lm.s); ΦV is the luminous flux (lm); *t* is the time interval.

1.4.4.1.5 Sky Models:

As users' demands and modelling techniques become more advanced, accurate input data has become crucial for building energy simulation models, especially for simulating solar heat gain and daylight availability (Perez, R., 1990; Antunes, H.S., 2016). Simulation of daylight distribution in complex interior spaces requires accurate knowledge of the distribution of light in the sky, despite the constantly changing sky conditions. Daylighting simulations typically use average sky conditions. To achieve this, various models of virtual skies have been developed by the Commission Internationale d'Éclairage (CIE) and others. However, only the both models CIE sky model and Perez et al. sky model are described in this section (Mardaljevic, J., 2000; Kensek, K. et al., 2011; Antunes, H.S., 2016). Firstly, the CIE has created 15 distinct sky conditions through mathematical development, as depicted in Figure 1.9. Overcast and clear skies, two of these sky conditions, have been widely utilized in daylighting simulations globally; The CIE clear sky is characterized by less than 30% cloud coverage or no clouds and varies based on the sun's altitude and azimuth. The sky is brighter when closer to the sun and dimmer when farther away. The model is valuable in visual glare and thermal discomfort research, as it allows for the consideration and calculation of direct sunlight inside a building (Perez, R., 1990; Antunes, H.S., 2016; Piderit, M. B., 2014; Kensek, K. et al., 2011). The CIE overcast sky model is frequently utilized to determine daylight factors, assuming a sky that is entirely cloud-covered and that sunlight is entirely obstructed by clouds (100% covered). Under such conditions, direct lighting is minimal to non-existent, and global and diffuse illuminance values are very similar. This sky model is often used by designers and users as a worst-case scenario (Perez, R., 1990; Antunes, H.S., 2016; Piderit, M. B., 2014; Kensek, K. et al., 2011).

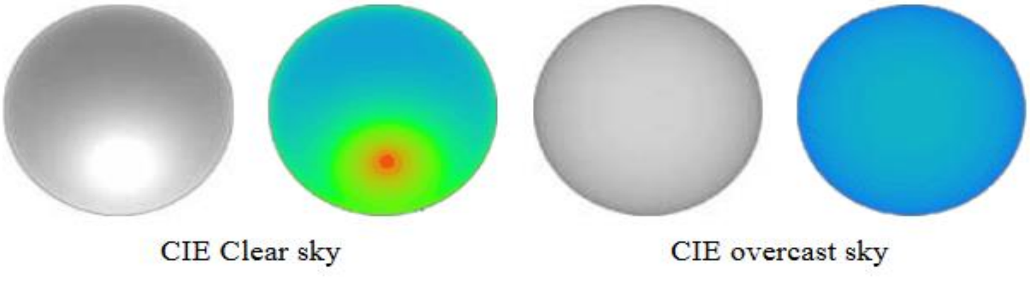


Figure 1.9: CIE Sky conditions. Source (Source: Kensek, K. et al., 2011; Sky Illuminance, 2010)

Secondly, regarding the Perez Sky Model is a highly utilized approach for determining the distribution of solar radiation and daylight in architectural spaces. It is based on empirical data derived from measurements of the sky's luminance and is categorized into four groups: clear, intermediate, hazy, and overcast. The model accounts for variables such as the sun's position, cloud cover, and the angle of incidence of radiation on various surfaces. It is especially valuable for designing and assessing the effectiveness of daylighting systems in buildings, as well as for predicting the amount of solar energy that can be collected from photovoltaic panels or other solar technologies (Mardaljevic, J., 2000; Perez, R., 1990; Antunes, H.S., 2016; Piderit, M. B., 2014; Kensek, K. et al., 2011).

The Uniform Luminance Model is the most basic sky model, which assumes a constant brightness throughout the sky and was originally designed to represent heavily overcast conditions. However, it has been recognized for some time that a heavily overcast sky actually exhibits a relative gradation from darker horizons to brighter zeniths, as documented as far back as 1901. Consequently, the Uniform Luminance Sky is an inadequate representation of any real-world meteorological conditions and is typically not utilized for illuminance modeling purposes (Mardaljevic, J., 2000). The CIE Standard Overcast Sky was adopted as a standard by the CIE in 1955 and is commonly used for illuminance modeling. It is normalized to the zenith luminance and has the form as shown below (see Equation 2.5) (Mardaljevic, J., 2000).

$$L\zeta = \frac{Lz(1+2cos\zeta)}{3} \tag{5}$$

Where; Lζ is the luminance at an angle; ζ from the zenith and Lz is the zenith luminance.

The CIE clear sky model, similar to the CIE overcast standard, is also normalized to zenith luminance. The luminance distribution of the sky is described by the following equation 2.6 below in this section.

$$L = L\zeta \frac{(0.91+10e^{-3\theta}+0.45cos^2\theta)(1-e^{(-032/sin\gamma)})}{(0.91+10e^{-3\left(\frac{\pi}{2}-\gamma s\right)}+0.45sin^2\gamma s)(1-e^{-0.32})} \tag{6}$$

Where; γ is the sky point altitude, γs is the solar altitude, and θ is the angle between the sun and the sky point. It is important to note that none of these models predict the spectral distribution of skylight, which refers to its color (Mardaljevic, J., 2000).

1.4.4.2 Conventional daylighting metrics (climate-based daylight metrics)

1.4.4.2.1 Daylight factor

The daylight factor (DF) is presently the most widely utilized daylight measure across the globe (Reinhart, C.F. and S., 2000; Mardaljevic, J. et al., 2009). According to Mardaljevic, J. defined this concept as: “The daylight factor at any point is the ratio of the interior illuminance at that point to the global horizontal illuminance under CIE standard overcast sky conditions” (Mardaljevic, J., 2000). Thereby, it is defined as the percentage of the indoor illuminance to the outdoor illuminance, expressed as a ratio, under overcast sky conditions. The DF represents the amount of daylight that is available inside a room compared to the amount of unobstructed daylight that is available outside, taking into account factors such as window size, orientation, and shading. It is a useful tool for assessing the quality of natural light in buildings and for informing design decisions related to glazing, shading, and other daylighting strategies (Mardaljevic, J., 2000; Karlsen, L. R., 2016). However, it is limited in its ability to account for daylighting design problems that vary with building location and orientation. In particular, many design problems may not be detected using DF alone, as noted by Reinhart, Mardaljevic, & Rogers (2006). Developed in 19th-century Britain as a legal standard for determining when a new building would encroach on the daylight of another, the daylight factor (DF) is the earliest metric for daylight assessment. An adequate DF is considered to be greater than 2%, while a well daylit space falls within the range of 2-5% (LEE, J., 2020; Yang, F., 2017; Karlsen, L. R., 2016). According to recent studies, the daylight factor (DF) is typically represented as the following percentage (Mardaljevic, J., 2000) :

$$DF = \frac{E_{in}}{E_{out}} * 100\% \tag{7}$$

The traditional approach for evaluating daylight factors, which is still widely used, involves measuring illuminance inside scale models under artificial sky conditions. Unlike thermal, acoustic, or structural models, physical models for lighting do not require any scaling corrections. Although a highly detailed physical model could offer accurate results, the construction cost of such models can be excessive, especially when evaluating multiple design variations. Consequently, architects and design consultants are increasingly utilizing computer simulations as a viable alternative (Mardaljevic, J., 2000). Regarding the health building facilities, according to Thomas (1996), the normal recommended minimum DF values in hospitals is 1%, and the average of values is 5% (Alzoubi et al. 2015).

Over the last decade, there has been an increasing demand for a new daylight metric to replace the DF, and significant effort has gone into developing climate-based daylight metrics that can be used as criteria for annual daylight assessments. Climate-based daylight modeling (CBDM) is based on meteorological data for sun and sky conditions (Mardaljevic, J., 2000; Reinhart, C.F. and S., 2000; Kittler, R. et al., 2010; Mardaljevic, J., 2006). According to these previous researches, some of the newly developed climate-based daylight metrics (CBDM) are shown in Table 2.3 (Karlsen, L. R., 2016).

Table 1.3: A set of recently created daylight metrics based on climate conditions (Karlsen, L. R., 2016)

Metric	Information in the metric	Lower threshold [lux]	Upper threshold [lux]	Comment	Reference
Daylight autonomy (DA)	Percentage of occupied time when a minimum work plane illuminance can be maintained by daylight alone.	500*	-	Threshold commonly derived from standards for artificial lighting.	[96]
Useful daylight illuminance (UDI)	Percentage of work hours when daylight levels are useful for the occupants.	100	2000 ** 3000***	Thresholds derived from literature study on occupant preferences in daylit offices. Upper limit is associated with glare/overheating.	[92, 97]
DA_{con} in combination with DA_{max}	Based on the DA criteria, but softener the threshold by attribute partial credits to time steps when the daylight illuminance lies below the minimum illuminance level.	500 *	10 times the design illuminance of a space	DA_{max} indicate occurrence of direct sunlight and potentially glary conditions.	[87, 98]
Spatial daylight autonomy 300/50% ($sDA_{300/50\%}$)	Percentage of analysis area that achieves the threshold of 300 lux for 50 % of the analysis period.	300	-	Target value of *300 lux* was derived from a survey with daylight experts and building occupants in 61 day lit spaces.	[93, 99]

* The value of 500 lux is valid for offices. ** 2000 lux is derived for offices, in places where the occupants have opportunity to adjust the settings higher illuminances may be accepted. *** 3000 lux has been proposed as the upper threshold in a recent publication by Mardaljevic et al. 2000 (Karlsen, L. R., 2016).

1.4.4.2.2 Daylight Autonomy (DA)

The Daylight Autonomy (DA) metric represents the ratio between the total number of occupied hours in a year and the number of hours when the daylight illuminance exceeds the minimum illuminance level required (Reinhart & Walkenhorst, 2001; Tabadkani, A. et al. 2018; Yang, F., 2017). Daylight autonomy (DA) is a type of a dynamic daylighting metric that takes into account the variations in illuminance over time, using solar radiation data for the building's location. Unlike static daylight metrics, which do not consider changes in daylight over time, dynamic daylight metrics like DA consider the daily variations of daylight as well as unpredictable weather conditions. This feature makes dynamic metrics like DA more advantageous for evaluating the performance of daylighting systems (Reinhart, Mardaljevic, & Rogers, 2006; Yang, F., 2017).

Although the Daylight Autonomy approach is often touted as an effective method for reducing electric lighting usage, recent research has found significant flaws in this approach. For instance, it does not properly account for the quality of light that falls below a certain threshold, and it fails to consider the amount by which the threshold was exceeded during specific time periods. As a result, it may be necessary to explore alternative approaches for achieving energy savings in office spaces. For example, it may be possible to reduce lighting usage by optimizing the position and type of light fixtures, or by introducing natural light sources that are better suited to the specific needs of the occupants (EN12464-1, 2011; Antunes, H.S., 2016; Yang, F., 2017).

1.4.4.2.3 Continuous Daylight Autonomy (cDA)

In order to address the limitations of the Daylight Autonomy approach, a new metric called Continuous Daylight Autonomy has been proposed. This approach takes into account the partial contribution of daylight to illuminating a space, rather than relying solely on a hard threshold. For example, if the required illuminance is 500 lux and only 300 lux are provided by daylight alone, a partial credit of 0.6 is given to that time step. The result is a softer transition between compliance and non-compliance with the illuminance requirements. Essentially, this metric acknowledges that even partial daylight contribution is still beneficial in terms of illuminating a space (Reinhart, Mardaljevic, & Rogers, 2006; Yang, F., 2017; Antunes, H.S., 2016). Rogers (2006) explained that the calculation of the natural light level in a specific area during occupancy hours is commonly performed. Although cDA is similar to DA, it produces a restricted result when the illuminance falls below the minimum requirement. The concept of Maximum Daylight Autonomy involves taking into account the potential for glare to occur, and it measures the percentage of hours when direct sunlight or extremely bright daylight is present during occupancy. A defined threshold for DAmax is set, which is ten times the design illuminance value for the particular space (Yang, F., 2017; Antunes, H.S., 2016).

1.4.4.2.4 Spatial Daylight Autonomy (sDA)

Spatial Daylight Autonomy (sDA) is a building performance metric that assesses the quantity and quality of daylight in the interior of a space. Unlike other metrics, sDA considers both the distribution and amount of illuminance throughout the area. It calculates the percentage of the floor area within a space that receives sufficient daylight to meet a specified illuminance threshold for a specified fraction of the year. This metric is valuable for evaluating daylight in spaces with intricate geometries or areas that are not directly exposed to windows (Yang, F., 2017; Pellegrino et al. 2017; LEE, J., 2020; Heschong et al., 2012). The sDA metric is determines the amount of daylight illuminating the indoor space at a threshold of 300 lux during more than 50% of the occupied hours. Unlike the Daylight Autonomy (DA), which provides information on illuminance at a specific point, sDA provides a single value representing the entire considered area.

1.4.4.2.5 Useful daylight illuminance (UDI)

UDI is a method that aims to determine the percentage of the total number of occupied hours during a year in which the illuminance at a specific point falls within an acceptable range, as well as the total number of those hours. The acceptable range is considered to be between 100 and 3000 lux at the work plane, while illuminances below 100 lux are considered too dim and may lead to visual discomfort due to lack of daylight, and illuminances above 3000 lux are deemed too bright and can cause glare and excessive amounts of daylight, as noted by John Mardaljevic (2015) and Nabil & Mardaljevic (2005). Mardaljevic (2012) suggests that UDI supplementary, referring to daylight illuminances between 100-300 lux, can be utilized as a primary source of lighting or combined with artificial lights. On the other hand, UDI-autonomous, which includes daylight illuminances between 300-3000 lux, is typically preferred, with artificial lighting being unnecessary. Hence, using the defined thresholds, UDI can be calculated based on three metrics. The first metric indicates the percentage of working hours when UDI was achieved between 100 lux and 2000 lux. The second metric represents the percentage of working hours when UDI fell short of the minimum threshold of 100 lux. The third metric measures the percentage of working hours when UDI exceeded the maximum threshold of 2000 lux (Mardaljevic, 2012; Yang, F., 2017). For patient rooms, the suggested UDI metric is between 100-300 lux, whereas the maximum recommended lighting level for such rooms is 300 lux.

1.4.4.2.6 Annual Sunlight Exposure (ASE)

The Annual Sunlight Exposure (ASE) is a building design and evaluation metric that evaluates the possibility of direct sunlight penetration into a space over a year. This metric considers several factors, including building orientation, shading devices, and window placement. The ASE metric is useful for assessing the potential for solar heat gain and glare, and for optimizing the use of daylighting to decrease the requirement for artificial lighting. Its primary aim is to achieve a balance between daylighting and solar control, maximizing the advantages of both while minimizing the disadvantages. This metric refers to the portion of an area that receives illumination above a certain threshold for a certain percentage of hours during a year. (Heschong et al., 2012; Yang, F., 2017).

1.4.5 Visual comfort and glare

1.4.5.1 Visual comfort definition

Firstly, the definition of visual comfort refers to the subjective feeling of visual well-being that is influenced by the lighting environment. It is often described as a personal response to the amount and quality of light present in a particular space at a specific time. Visual comfort is a significant factor in both occupant satisfaction and work productivity. (Gadelhak, M. A. A, 2019; Andersen, A. et al., 2014). According to Boyce et al. (2003), a successful daylighting design should offer a significant amount of light that is free from glare. Conversely, a flawed design will result in either inadequate lighting, leading to frequent use of electric lighting, or too much light accompanied by glare. In addition, our daily activities involve diverse visual tasks that impose varying demands on the lighting provided (Andersen, A. et al., 2014; Boyce et al., 2003). The aim of designing for visual comfort is to establish an environment that facilitates visual tasks without causing unnecessary pressure or discomfort to the eyes (Tekce, I. et al., 2020). This can be accomplished by meticulously selecting and positioning lighting fixtures, utilizing suitable colors and materials, and taking into account the requirements and desires of occupants. Visual comfort is a significant component of the comprehensive indoor environmental quality (IEQ) and can have an effect on the health, wellness, and productivity of occupants (Gadelhak, M. A. A, 2019; Andersen, A. et al., 2014; Tekce, I. et al., 2020).

1.4.5.2 Parameters affecting visual comfort

While it is simple to recognize a comfortable environment, describing a visually comfortable environment can be challenging since the impact of "well-being" and "satisfaction" levels is not a singular effect, but rather a general state of human well-being. The elements that contribute to the visual well-being of individuals within a built environment are known as parameters of visual comfort. These parameters include several factors such as light quality and quantity, lighting distribution, Surface reflectance, color temperature, contrast, uniformity, and glare. Additionally, other variables related to the built environment such as geometry, window orientation, size of the space, and tasks performed within it can also affect visual comfort. It is crucial to consider all of these parameters when designing a space to guarantee that occupants feel visually comfortable (Giarma, C. et al., 2017; Fakhari,M. & Fayaz, R., 2023; TERI, 2021).

1.4.5.3 Glare

Glare is typically categorized into two types, disability glare and discomfort glare. As per the CIE vocabulary, disability glare refers to the type that makes an individual unable to see specific objects in a scene, while discomfort glare causes discomfort without necessarily affecting visual performance or visibility (Karlsen, L. R., 2016; Fry, G.A. and V.M. King, 1975; Ruck, N.C. et al., 2000). Glare is a perception of vision that arises when the level of light entering the eye becomes intolerable. It can result from the reflection or direct exposure to natural sunlight or artificial light sources, and it can have negative effects on visual performance and cause discomfort or even disability. Discomfort glare can produce a sense of unease without influencing visibility, while disability glare can hinder the ability to see certain objects within a given environment. To assess glare, different metrics, such as the Daylight Glare Index (DGI) or Daylight Glare Probability (DGP), can be used (Karlsen, L. R., 2016). Vos J.J. (2003) proposes that the current knowledge on discomfort glare includes two distinct phenomena: discomfort glare and dazzling glare. Discomfort glare is described by Vos as the presence of distracting lights that interfere with the foveal vision, while dazzling glare refers to the experience of bright light sources that cause the eyes to squint or avoid looking directly at them (Vos J.J., 2003; Karlsen, L. R., 2016; Osterhaus, W.K.E., 2005; Clear, R., 2013).

Although discomfort glare is a subjective experience, there have been many attempts to predict it objectively, leading to the creation of several glare indexes. These indexes include the CIE glare index (CGI), Daylight glare index (DGI), Unified glare rating (UGR), and Daylight glare probability (DGP). Out of all the glare metrics mentioned earlier, only two, namely DGI and DGP, are designed specifically for assessing daylight glare (Wienold, J. & J. Christoffersen, 2006; Hopkinson, R.G., 1972; Einhorn, H.D., 1969; Karlsen, L. R., 2016).

1.4.5.3.1 Daylight glare probability metric (DGP)

Daylight glare probability (DGP) is a measure used in the design and assessment of buildings to evaluate the possibility of visual discomfort resulting from glare caused by daylighting systems. It estimates the likelihood of glare at a particular location in a room during occupied hours, considering various factors such as window size and location, building orientation, and the surroundings. The objective of DGP is to enhance the design of daylighting systems in a way that minimizes the possibility of visual discomfort due to glare, while also maximizing the benefits of daylight (Karlsen, L. R., 2016). The DGP metric was developed by Wienold and Christoffersen (2006) based on real daylight conditions user assessments. They combined the existing CGI algorithm with an empirical approach (Konstantzos and Tzempelikos, 2014; Karlsen, 2016) to develop the DGP calculation formula, which is expressed as the following Equation (2.8):

$$DGP = 5.87 \cdot 10-5Ev + 9.18 \cdot 10-2log\ (1 + \Sigma \mathrm{i}\ (Ls, 2\ \omega s,\mathrm{i})/(Ev\ 1.87Pi\ 2) + 0.16 \qquad (8)$$

1.4.5.3.2 Daylight glare index (DGI)

The Daylight Glare Index (DGI) is a measure employed to assess the possibility of glare arising from daylighting systems within a building. The Daylight Glare Index (DGI) is a widely used metric to assess the degree of protection against glare. It was first introduced by Hopkinson (1972) and Hopkinson's DGI is included in the China national standard "GB 50033-2013 Standard for Daylighting Design of Buildings" that is employed to evaluate visual comfort levels (see Equation 2.9) (Wang, T. et al., 2022; Karlsen, L. R., 2016).The DGI is a key component of overall indoor environmental quality (IEQ), which plays a critical role in human health, well-being, and productivity in indoor spaces. A study analyzing visual comfort in office environments through a case study approach found that vertical eye illuminance performed better than complex glare indices in terms of overall IEQ (Wang, T. et al., 2022; Kevin Van Den Wymelenberg & Mehlika Inanici, 2014; Irfan Ullah, 2014).

$$DGI = 10 \cdot log10\ 0.48\ \Sigma\ (Ls\ 1.6\Omega s\ 0.8)/\ (Lb + 0.07\omega s\ 0.5Ls) \qquad (9)$$

1.4.6 Building and energy

Energy performance metric (EUI)

The energy crisis that occurred in the 1970s brought about concerns for the conservation of energy and the utilization of renewable energy sources. As energy production is linked to air pollution and global climate, it can contribute to the spread of certain diseases (Brown, Henze,

& Milford, 2017), and therefore the need for sustainable and eco-friendly practices has become increasingly important. Over the past few decades, global energy consumption in buildings has surged, and this trend is projected to continue in the future. Based on EIA's (2016) findings, it is anticipated that energy consumption in buildings will rise by an average of 1.5% each year from 2012 to 2040. According to a report by D&R International in 2012, the buildings sector in the United States consumed approximately 41% of the total energy in 2010, which is significantly higher than the transportation sector by 44% and the industrial sector by 36% (Yang, F., 2017). Buildings utilize energy for a variety of purposes such as lighting, heating, cooling, and running electrical equipment and systems. The growing energy consumption in buildings has major environmental consequences, including increased greenhouse gas emissions and a contribution to climate change. Governments and organizations are increasingly emphasizing the promotion of energy-efficient buildings and reduction of energy consumption through the implementation of renewable energy sources and energy-efficient technologies. The objective is to construct sustainable buildings that are environmentally responsible, economically feasible, and comfortable for occupants. According to research by the International Energy Agency (IEA), buildings are responsible for 36% of global final energy consumption and nearly 40% of total CO2 emissions (Yang, F., 2017).

In order to assess the energy efficiency of buildings, it is essential to compare the building performance metrics that are either calculated or measured to some reference values. These reference values may depict the energy-related features of building components or the energy consumption of building systems. According to Borgstein, Lamberts, & Hensen (2016) and Yang, F. (2017), this comparison is necessary to accurately evaluate the energy performance of buildings. A more frequent practice in assessing building performance is to utilize energy consumption metrics that normalize the whole-building energy, such as Energy Use Intensity (EUI) (Borgstein, Lamberts, & Hensen, 2016; Yang, F., 2017).

Energy Use Intensity (EUI) is a measurement used to assess the energy efficiency of a building by dividing its total energy consumption during a specific time period by its overall floor area. It is measured in energy units per square foot or square meter. EUI is typically utilized as a standard for comparing the energy performance of various buildings and identifying opportunities for enhancing building design, construction, and operation. A lower EUI value implies higher energy efficiency and lower energy usage, whereas a higher EUI value indicates lower energy efficiency and higher energy usage (EPA, 2023; Yang, F., 2017).

1.5 Measuring Daylight

The human eye and brain have the natural ability to adapt to changes in light sensitivity, as noted by Boyce (2003) and Nicol et al. (2006). Additionally, individual preferences and perceptions of light can vary greatly, as stated by Boyce (2003) and Galasiu & Veitch (2006). As a result, evaluating light quality can be challenging due to the variability and subjectivity of individual perceptions and preferences. A commonly used method for evaluating if there is enough daylight in an office is to measure or simulate the amount of light at the workplane level. This approach became prevalent at the same time as the methods used by the electrical lighting industry in the early 1900s, when tasks requiring visual clarity were often performed on a horizontal work surface (Boyce, 2003; Konis, K. S., 2012; Hellinga, HY., 2013; Brembilla, E., 2017; Knoop, M., 2016; Mardaljevic, J., 2000). Previously, the daylight factor (DF) and Illuminance measure have been the most commonly used metrics to evaluate whether a space has sufficient daylight. This is based on the measurement of horizontal illuminance at the work plane and has been widely used in codes and standards in Europe, the UK, and previous versions of the LEED rating system. The DF method is favored due to its simplicity and ease of measurement, as noted by Nabil and Mardaljevic (2005) (Konis, K. S., 2012; Hellinga, HY., 2013). As a result, various approaches have been proposed to replace the DF method with the aim of offering a more efficient way to determine which areas have enough daylight, as well as distinguishing between areas that have comfortable and uncomfortable levels of daylight illumination (Konis, K. S., 2012). Various recent studies have indicated that people generally prefer higher levels of illuminance in workspaces than the recommended standards (Fleischer et al. 2001; Veitch & Newsham, 2005; Vischer, J.C., 2007). According to Fleischer et al. (2001), the more illuminance in a workspace, the more the workspace is rated as pleasant. However, higher illuminance levels do not necessarily lead to better individual performance (Hellinga, HY., 2013).

In addition, the psychological element of daylight perception is an essential aspect that cannot be disregarded. Subjective assessment criteria, as outlined by Fontoynont (2002), can be utilized to explore this aspect. In particular, Post Occupancy Evaluations (POE) can offer valuable insights into how individuals perceive the quality of light in real work environments. By comparing the results of questionnaires that evaluate the human assessment of lighting to quantitative measures of lighting, such as illuminance and luminance levels, valuable information can be obtained (Hellinga, HY., 2013; Knoop, M., 2016). Boyce, Veitch, Newsham, Myer and Hunter (2003) conducted a study to investigate how light intensity affects patients' experiences of visual and physical discomfort. To assess visual discomfort, participants completed a questionnaire that examined how light intensity affects eye discomfort. To assess physical discomfort, another questionnaire was given that evaluated how light intensity affects several physical symptoms, such as a sore throat, sore back, and excessive mental fatigue (Pennings, E., 2018). Finally, Dianat, Sedghi, Bagherzade, Jafarabadi, and Stedmon (2013) conducted a survey to assess the satisfaction of hospital staff with the lighting environment. The study aimed to determine the level of satisfaction with lighting in hospitals by using a survey consisting of questions related to lighting, which had been previously developed for the work environment and was adapted for use in hospitals (Pennings, E., 2018).

1.6 Existing daylight facade systems and technologies

1.6.1 Windows and glazing

A window is an aperture in a building's wall that permits light and usually air to enter the interior. There are two main types of windows: firstly, those set into a building's walls and secondly, openings in the roof that provide access to the sky, which are also called skylights. Therefore, in this context, windows specifically refer to the windows on a building's façade (Mohamedali, Ahmed, 2017; Sobhani, E. R., 2019). The main goals of window design are as follows:

- Allow natural daylight to enter into the building,
- Optimize the advantages of daylighting,
- Provide sound insulation under normal circumstances,
- Ensure thermal insulation, and
- Enable ventilation without causing draughts.

The properties of windows make it possible for occupants to control the indoor environment, and this is a critical factor in determining user satisfaction. This demonstrates how architecture can take the lead in meeting the needs of indoor spaces. Philips (2004) described the importance of windows in building design, stating that they can provide color, sunlight, shading, views, and orientation. With the increasing importance of energy efficiency in building design, window design has moved towards high-tech solutions that address issues such as direct sunlight, glare, ventilation, solar gain, pollution, and noise. Advances in window design have made air conditioning optional. In creating a balance between maximum visual comfort and environmental considerations, it is essential to recognize the reality of environmental issues such as greenhouse gas emissions and global warming (Mohamedali, Ahmed, 2017; Sobhani, E. R., 2019).

The primary goal of using glazing in building design is to allow natural light to enter the indoor spaces and to create a connection between the interior and exterior environments. In addition, people tend to appreciate the various natural components, such as color, light, and shade, of their surroundings. This appreciation can be achieved through the use of glass in windows or facades, according to Phillips (2004) and Mohamedali, Ahmed (2017). There are various glazing types available for windows nowadays. As a result, it is crucial for the architect, in collaboration with the services and lighting specialist, to consider the performance specification, which includes factors such as the window's alignment, thermal properties, acoustic features, solar shading capacity, and ventilation. The window's primary functions of allowing daylight into the interior space and providing a view of the exterior must also be taken into account. Additionally, the decision whether to use fixed or open windows should be based on the ventilation requirements. If a glazing type significantly reduces the amount of daylight entering the interior and darkens both the interior and exterior views, the building's façade would appear dark from the outside. While humans naturally appreciate the natural environment, certain modifications may prove unsatisfactory. In residential buildings, for example, dark glass applied to the façade can make the interior appear dreary. The three fundamental categories of glazing are described below (Phillips, 2004; Sobhani, E. R., 2019).

1. **Clear glazing:** This glazing type consists of thick glass, either single or double, which can decrease the amount of daylight admitted when the thickness or number of sheets is increased. However, it gives a natural appearance of the exterior color. Clear glass allows for both high daylight transmission and high solar radiation. In order to reduce the thermal gain of sunlight and maintain high daylight transmission, high-tech glasses have been developed (Phillips, 2004; Sobhani, E. R., 2019).
2. **Tinted glass:** This can be classified into two types. The first type involves the modification of clear glass to incorporate radiant thermal diffusion characteristics. In this regard, thicker glass has a lower diffusion rate, which leads to better control of sunlight radiant heat. The second type involves the use of glazing coated with fine layers of specific materials, typically metallic oxides, to reduce heat transmission from the building. These coatings are applied to the inner layer of the double-glazed piece for safety purposes, and they may be easily destroyed. Coated glasses are designed to transmit natural light and offer a clear view. However, they are also quite expensive and are typically specified on demand (Phillips, 2004; Sobhani, E. R., 2019).
3. **Miscellaneous glazing:** This section discusses various types of glazing that cannot be easily classified into a single category. The fourth types are wired glass, patterned glass,

and laminated glass, and glass blocks; which explained in detail below (Phillips, 2004; Sobhani, E. R., 2019):

- **Patterned glass** is a type of semi-molten glass used primarily for decorative purposes. Its light transmission capacity can be adjusted, which is why it is not commonly used for windows.
- **Wired glass** is produced by sandwiching wire mesh within the glass. It is mainly used for security situations.
- **Laminated glasses:** This type of glazing is produced by sandwiching layers of plastic laminate between layers of glass. It also has security uses. It is frequently used in museums where objects on display are exposed to daylight, and to regulate the amount of UV light entering the building.
- **Glass blocks:** These were popular in the 1930s. Their hollow structure gives them thermal properties. They are still in use today as they allow for the introduction of daylight into new buildings, as long as suitable openings are provided (Phillips, 2004; Sobhani, E. R., 2019).

1.6.2 Solar shading systems

There are various types of solar shading, each with its advantages and disadvantages. The architect needs to be aware of the factors that determine the appropriate type of shading for the building. The main reasons for incorporating shading into the building design are to: 1) reduce the impact of heat gain from solar radiation, 2) prevent glare caused by direct sunlight entering through windows, and 3) provide additional privacy (Tzempelikos, 2017; Ruck, N.C. et al., 2000 ; Mohamedali, Ahmed, 2017; Sobhani, E. R., 2019; Karlsen, L. R., 2016). According to Nielsen et al. (2011), solar shading systems can either be static or dynamic, but their investigation suggests that dynamic solutions perform better than static ones in a Danish climate. This is supported by evidence that dynamic shading systems are more effective in reducing energy demand and overheating, while still allowing for daylight supply and outside views when shading is not needed. Winther (2013) and Liu (2014) also agree that implementing dynamic solar shading on buildings in Denmark leads to improved building performance, and that intelligent dynamic facades will be crucial for achieving high building performance in the future (Karlsen, L. R., 2016).

There are various types of external shading systems available, such as light shelves, overhangs, canopies, shutters, louvers (fixed and movable), deep window reveals, vertical fins, egg crate baffles, and roller blinds. When selecting any of these methods, the most important factor to consider is the feasibility and effectiveness of the hardware involved. Additionally, architects may also need to take into account the building's exterior appearance. Although it is important to control solar heat gain by manipulating it before it enters the building, external shading methods can be susceptible to damage. Other types of external shading systems include awnings, continental shutters, and external roller blinds. To ensure cost-effectiveness, a comparison should be made with internal shading systems. Furthermore, architects should consider the visual appearance of the building's elevation before making a decision on which system to use (Sobhani, E. R., 2019; Karlsen, L. R., 2016). In addition, Diffuse light strategies aim to distribute skylight to the interior in the absence of direct sunlight during cloudy conditions. In such situations, windows and skylights are specifically designed to allow daylight into the room. However, during sunny conditions, openings on the wall can cause overheating and glare, making sun shading and glare protection systems essential. Depending on the design strategy, different shading systems that transmit either diffused skylight or direct sunlight may be used. Additionally, daylight can be enhanced by incorporating architectural measures such as reflective sills. It is important to note that window design plays a significant role in the performance of diffuse light strategies during cloudy situations (Ruck, N.C. et al., 2000 ; Mohamedali, Ahmed, 2017; Sobhani, E. R., 2019; Karlsen, L. R., 2016). According to Ruck, N.C. et al. (2000) and Sobhani, E. R. (2019) were described below the Tables 1.4, 1.5, 1.6 and 1.7 that lists the different types of solar shading systems and show which climate they are suitable for, and where are normally placed in the building.

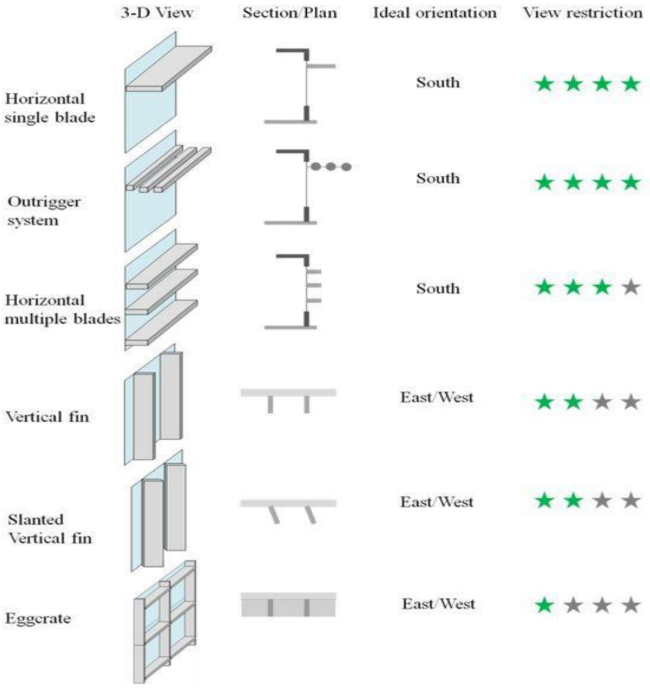
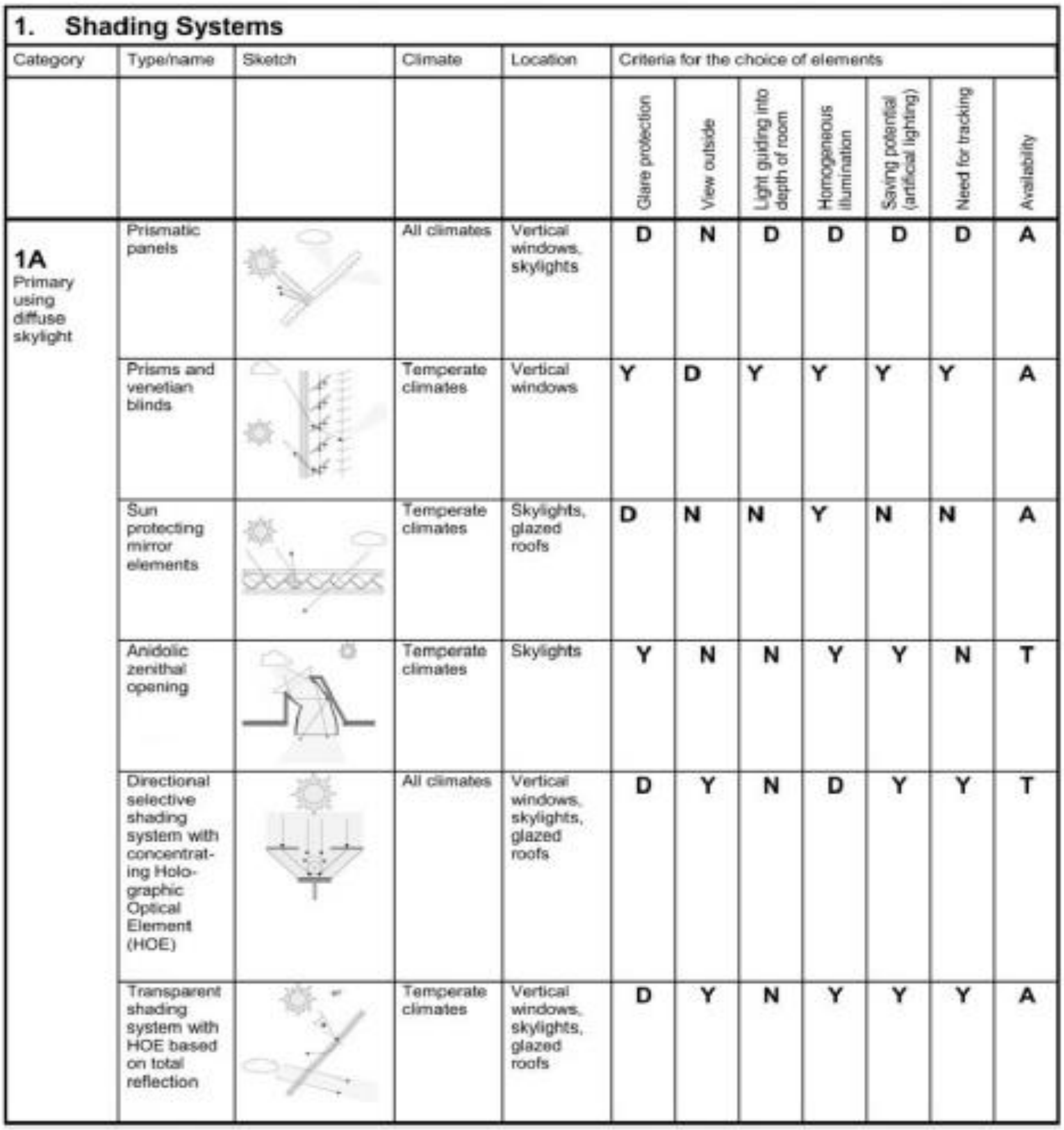


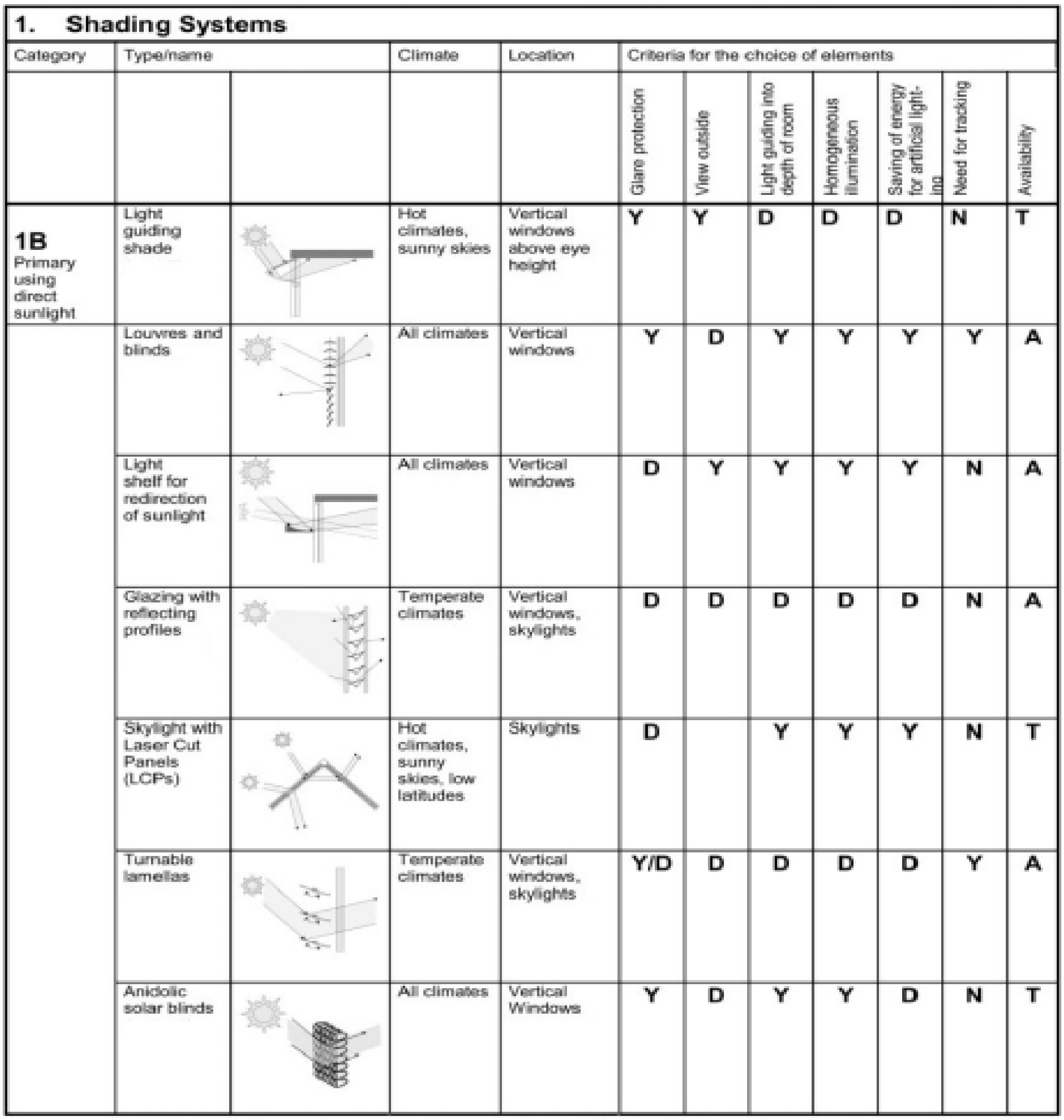
Figure 1.10: Fixed and movable solar shadings (Source: Tzempelikos and Athienitis, 2007)

Table 1.4: Types of daylighting systems: with shading (1A &1B) and without (2A-2D) (abbreviations in table: Y=yes, D-depends, N=no, A=available, T=testing phase) (Source: Ruck et al., 2000)



1. Shading Systems											
Category	Type/name	Sketch	Climate	Location	Criteria for the choice of elements						
					Glare protection	View outside	Light guiding into depth of room	Homogeneous illumination	Saving potential (artificial lighting)	Need for tracking	Availability
1A Primary using diffuse skylight	Prismatic panels		All climates	Vertical windows, skylights	D	N	D	D	D	D	A
	Prisms and venetian blinds		Temperate climates	Vertical windows	Y	D	Y	Y	Y	Y	A
	Sun protecting mirror elements		Temperate climates	Skylights, glazed roofs	D	N	N	Y	N	N	A
	Anidolic zenithal opening		Temperate climates	Skylights	Y	N	N	Y	Y	N	T
	Directional selective shading system with concentrating Holographic Optical Element (HOE)		All climates	Vertical windows, skylights, glazed roofs	D	Y	N	D	Y	Y	T
	Transparent shading system with HOE based on total reflection		Temperate climates	Vertical windows, skylights, glazed roofs	D	Y	N	Y	Y	Y	A

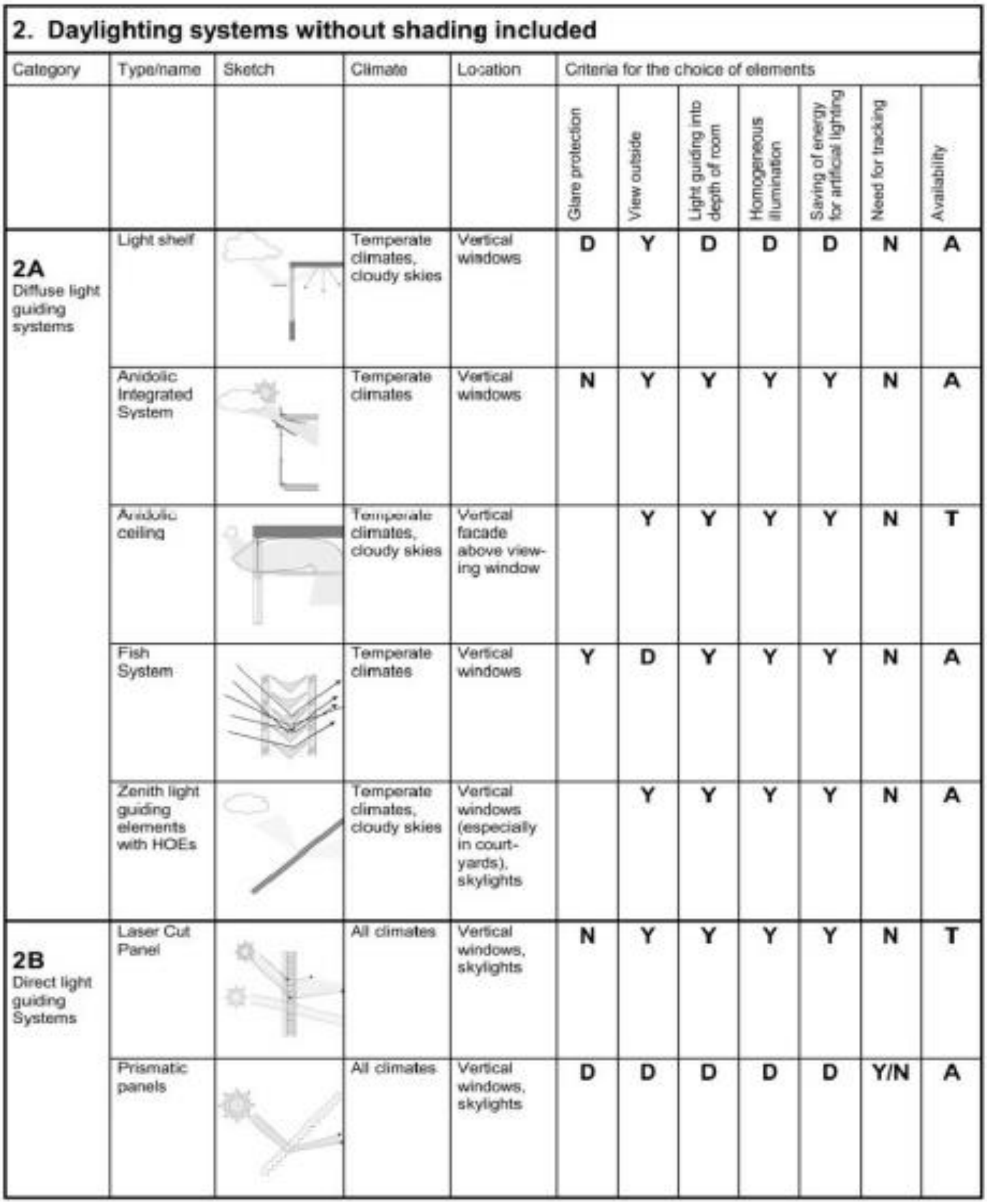
Table 1.5: Types of daylighting systems: with shading (1A & 1B) and without (2A-2D)
(abbreviations in table: Y=yes, D=depends, N=no, A=available, T=testing phase)
(Source: Ruck et al., 2000)



1. Shading Systems

Category	Type/name		Climate	Location	Criteria for the choice of elements						
					Glare protection	View outside	Light guiding into depth of room	Homogeneous illumination	Saving of energy for artificial lighting	Need for tracking	Availability
1B Primary using direct sunlight	Light guiding shade		Hot climates, sunny skies	Vertical windows above eye height	Y	Y	D	D	D	N	T
	Louvres and blinds		All climates	Vertical windows	Y	D	Y	Y	Y	Y	A
	Light shelf for redirection of sunlight		All climates	Vertical windows	D	Y	Y	Y	Y	N	A
	Glazing with reflecting profiles		Temperate climates	Vertical windows, skylights	D	D	D	D	D	N	A
	Skylight with Laser Cut Panels (LCPs)		Hot climates, sunny skies, low latitudes	Skylights	D		Y	Y	Y	N	T
	Turnable lamellas		Temperate climates	Vertical windows, skylights	Y/D	D	D	D	D	Y	A
	Anidolic solar blinds		All climates	Vertical Windows	Y	D	Y	Y	D	N	T

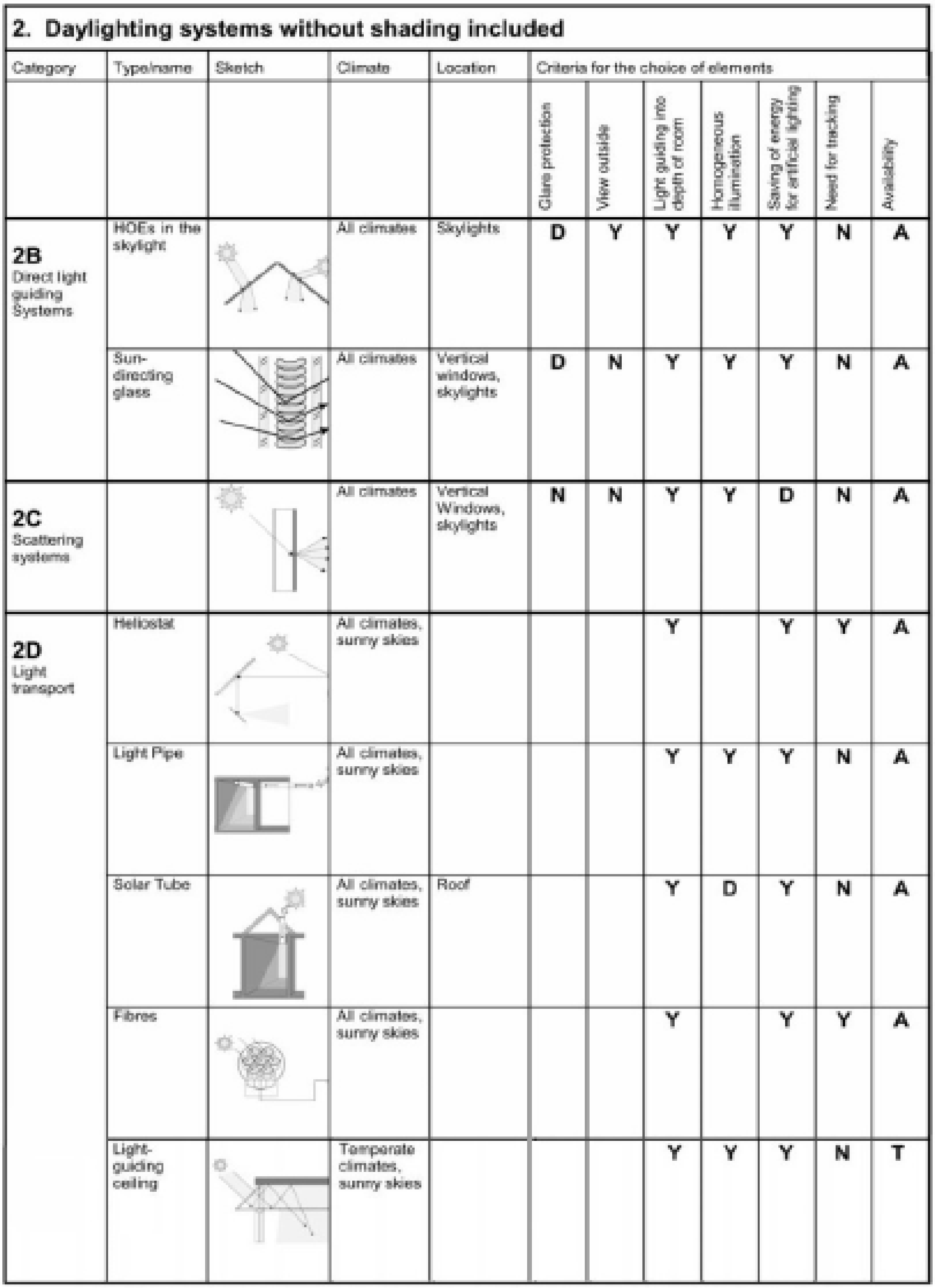
Table 1.6: Types of daylighting systems: with shading (1A &1B) and without (2A-2D) (abbreviations in table: Y=yes, D=depends, N=no, A=available, T=testing phase (Source: Ruck et al., 2000)



2. Daylighting systems without shading included

Category	Type/name	Sketch	Climate	Location	Criteria for the choice of elements						
					Glare protection	View outside	Light guiding into depth of room	Homogeneous illumination	Saving of energy for artificial lighting	Need for tracking	Availability
2A Diffuse light guiding systems	Light shelf		Temperate climates, cloudy skies	Vertical windows	D	Y	D	D	D	N	A
	Anidolic Integrated System		Temperate climates	Vertical windows	N	Y	Y	Y	Y	N	A
	Anidolic ceiling		Temperate climates, cloudy skies	Vertical facade above viewing window		Y	Y	Y	Y	N	T
	Fish System		Temperate climates	Vertical windows	Y	D	Y	Y	Y	N	A
	Zenith light guiding elements with HOEs		Temperate climates, cloudy skies	Vertical windows (especially in courtyards), skylights		Y	Y	Y	Y	N	A
2B Direct light guiding Systems	Laser Cut Panel		All climates	Vertical windows, skylights	N	Y	Y	Y	Y	N	T
	Prismatic panels		All climates	Vertical windows, skylights	D	D	D	D	D	Y/N	A

Table 1.7: Types of daylighting systems: with shading (1A &1B) and without (2A-2D) (abbreviations in table: Y=yes, D=depends, N=no, A=available, T=testing phase) (Source: Ruck et al., 2000)



2. Daylighting systems without shading included

Category	Type/name	Sketch	Climate	Location	Criteria for the choice of elements						
					Glare protection	View outside	Light guiding into depth of room	Homogeneous illumination	Saving of energy for artificial lighting	Need for tracking	Availability
2B Direct light guiding Systems	HOEs in the skylight		All climates	Skylights	D	Y	Y	Y	Y	N	A
	Sun-directing glass		All climates	Vertical windows, skylights	D	N	Y	Y	Y	N	A
2C Scattering systems			All climates	Vertical Windows, skylights	N	N	Y	Y	D	N	A
2D Light transport	Heliostat		All climates, sunny skies				Y		Y	Y	A
	Light Pipe		All climates, sunny skies				Y	Y	Y	N	A
	Solar Tube		All climates, sunny skies	Roof			Y	D	Y	N	A
	Fibres		All climates, sunny skies				Y		Y	Y	A
	Light-guiding ceiling		Temperate climates, sunny skies				Y	Y	Y	N	T

Innovative Façade Systems

Adaptive architecture refers to a type of architecture that has the ability to modify the physical attributes of a building in a predetermined manner to adapt to changing external and internal factors. These physical attributes can include the form, shape, color, texture, acoustic properties, and porosity of the building, among others. The changing factors can include temperature, relative humidity, precipitation, wind, sound, solar radiation, Co2-level, as well as user activities, needs, and social contexts, as stated by Schnädelbach and March (2010) (Sobhani, E. R., 2019). Innovative systems such as newly-developed devices, materials, and adaptive facades are being used to enhance daylight utilization and control. These systems aim to improve conventional daylighting techniques by utilizing new optical materials, elements, and devices, including overhangs, light shelves, blinds, screens, and light filters. These advanced daylighting systems are designed to deliver direct daylight into remote and windowless deep spaces in buildings, while also maximizing the use of available daylight in indoor environments (Giovannini et al., 2015; Sobhani, E. R., 2019). The main goal of innovative daylighting systems is to enhance the distribution of daylight in a given space while also controlling direct sunlight. Various innovative systems have been developed to achieve this goal, including mirrors, prismatic glazing, and adaptive facades. Among these systems, adaptive facades have gained significant global attention over the past decade (Giovannini et al., 2015; Sobhani, E. R., 2019). Adaptive building shells are designed to react to three main factors: (1) the environment, (2) users, and (3) objects, as stated by Schnädelbach and March (2010). Building shells can respond to environmental factors such as daylight, rain, and wind, and this can lead to improved building performance by allowing for proper daylighting and reduced energy consumption, which aligns with the goal of environmental sustainability. Additionally, building shells can be designed to cater to the needs of the users, and the architectural layout can be changed either manually or automatically. According to Schnädelbach (2010), while it is less common, adaptive facades can also be designed to respond to objects.

The fenestration and glazing properties of a building play a crucial role in determining its thermal and lighting comfort, energy efficiency, and privacy. The windows, solar shading, skylights, and other innovative design features of a building's façade are essential for controlling and utilizing daylight. These elements come in various types and designs, and therefore, it is vital to select and arrange them properly to improve the quality of the indoor environment in terms of visual comfort. The objective of the architect in daylighting is to integrate façade elements in a way that minimizes glare, direct sunlight, and heat gain (Sobhani, E. R., 2019; Karlsen, L. R., 2016).

1.7 Conclusion

The utilization of daylight not only enhances the visual quality of indoor environments by improving lighting conditions and adding aesthetic features that change the perception of the space, but it also provides non-visual benefits. The condition of daylighting is strongly linked to the physical and mental health of occupants. Based on findings in the literature review of this chapter the optimal utilization of daylight can significantly enhance the quality of life for building occupants. To achieve this, it is crucial to apply effective strategies for controlling and utilizing daylight. As discussed earlier, the design phase plays a critical role in determining the criteria for visual comfort. To meet these criteria, several factors need to be considered during the planning phase of daylighting.

This chapter offered an overview of the research on daylight, daylight environmental ambiances related to indoor space quality, and its relation with human health and the well-being, finally basic fundamental concepts and parameters of daylight quality and visual comfort in health buildings.

CHAPTER 2

PARAMETRIC DESIGN AND GENETIC ALGORITHMS APPROACH: BACKGROUND

2.1 Introduction

> “ … *Instead of trying to solve new problems with old forms, we should develop the new forms from the very nature of the new problems….*”
>
> (Ludwig Mies van der Rohe)

In modern architectural design, the factor of performance has become a crucial aspect. The term "performance" is encompassing, as there are numerous approaches to assessing a building's effectiveness, efficiency, and overall user experience. The use of building performance simulations has become a widespread practice among building experts to assess various design alternatives prior to construction, as noted by Hong et al. (2000). As a result, novel computational methods and techniques have emerged to simplify the design process of contemporary intricate buildings, and to establish a meaningful quantitative connection between the environment and the building envelope, while also considering the factors that affect building design. This has led to the development of the concept of parametric design in architecture, which aims to address complicated designs and attain more precise outcomes.

Within this framework, the following section provides a comprehensive overview of the current collection of literature on parametric analysis and genetic algorithms optimization of buildings approach. Initially, we introduce some fundamental concepts that are beneficial in comprehending the theoretical principles and methodologies of this particular approach. Subsequently, we present an outline of research studies that have employed the multi-objective genetic algorithm approach, with a particular focus on those conducted during the initial design phase. The objective is to provide a comprehensive workflow of the multi-objective optimization process based on genetic algorithms, which aims to accomplish various and potentially conflicting objectives for specified issues.

2.2 Parametric design

2.2.1 Definition

All elements and proportions of the architectural design can be deemed as parameters in the broader context, including aspects like position, alignment, structure, solar exposure, and the like. In the traditional design process, if the designer wishes to modify any parameter once the initial model is established, the entire process must be redone, resulting in a time-intensive undertaking (Eltaweel, A. & SU, Y., 2017). Thus, any modifications or advancements made to the parameters will be automatically and instantly reflected in the model, representing a "shortcut" to the final product. Figure 2.1 illustrates a visual contrast between the traditional approach and parametric design.

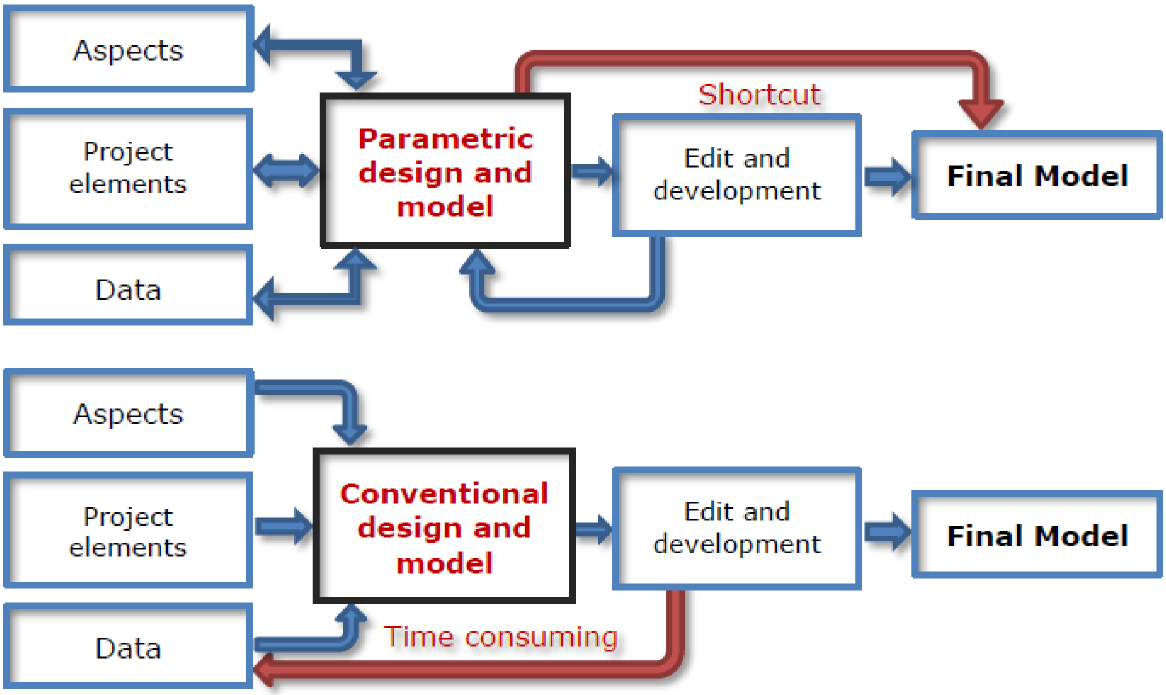


Figure 2.1: A comparative illustration depicting the disparity in time consumption between the parametric design process and traditional design methods
(Source: Eltaweel, A. & SU, Y., 2017)

The roots of parametric design can be traced back to generative design. Building upon these fundamental generative design principles, parametric design has developed into one of the most extensively used generative design methodologies in both practical and educational settings (N. Gu et al., 2018). Parametric modelling or design refers to a technique that enables the generation of multiple building model design options by establishing a series of relationships between the geometric components. These entities are depicted using variables and functions that link them together. This approach empowers the designer to modify the variable values to create a variety of alternatives, bypassing the time-consuming traditional process that requires starting the design from scratch for every change. Conversely, in parametric modelling, the initial design is established by a predefined set of variables from which an entire range of options can emerge. The crucial aspect of developing a parametric model lies in defining the design constraints and the underlying logic that governs the modification of parameters (Ahmed AbdelAziz, F.M.F., 2016; Khelil, S., 2020). In the realm of architecture, parametric design pertains to the modeling of building shapes through the utilization of parameters and functions. This approach draws inspiration from computer science programming technologies. While it retains the flexibility of programming, its user interface is more visually oriented, making it more accessible than conventional programming languages (Niclas, 2019; Yang, F., 2017). Parametric modeling provides the opportunity to generate diverse solutions with varying attributes, but challenges arise when the search space is extensive. This presents an issue of how to evaluate and select the multitude of alternatives based on performance criteria. This is a tedious process that may take a considerable amount of time without arriving at a satisfactory outcome. Consequently, there is a necessity to employ an algorithm that aims to optimize the performance criteria. The algorithm endeavors to establish the relationship between geometric attributes and performance, aiming to minimize or maximize a designated objective function to attain an optimal or near-optimal solution (Ahmed AbdelAziz, F.M.F., 2016; Khelil, S., 2020; Niclas, 2019; Yang, F., 2017). Parametric design allows for the exploration of numerous building outcomes in a virtual space before being executed in reality. A simple illustration of parametric design is displayed in Figure 2.2 which illustrates the process of creating a box-shaped object using parametric design, which involves three functions and three parameters. These parameters determine the dimensions of the box, including its width, depth, and height. By altering these parameters, a range of box geometries can be generated.

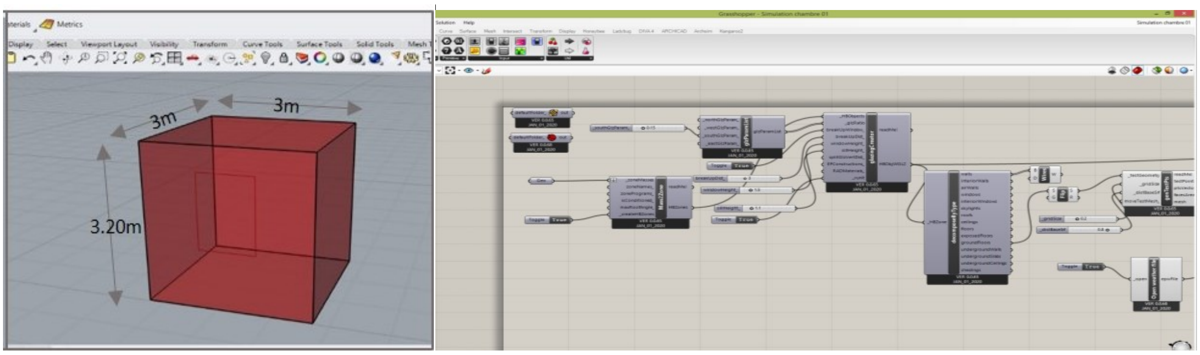


Figure 2.2: Box room model parameters in Rhinoceros software (Source: Author, 2022)

The fusion of parametric design and building performance evaluation tools enables the creation of design alternatives based on specific performance criteria, such as lighting performance, structural performance, and energy performance. Rolvink, van de Straat, and Coenders (2010) conducted research on building structural systems using parametric approaches and demonstrated how parametric design can aid in generating design alternatives. Labib (2015) utilized parametric design methods to investigate the geometry of light shelves and ceilings and evaluated designs based on their daylighting performance (Yang, F., 2017; Ahmed AbdelAziz, F.M.F., 2016; Niclas, 2019). Parametric modelling and parametric design are not interchangeable terms. While both involve the use of parameters to create design alternatives, they have different objectives. Parametric modelling focuses on establishing a set of parameters that form a logical relationship between design elements. On the other hand, parametric design is a creative process that aims to achieve complex and aesthetically pleasing forms. The observer may perceive the design as complex, even though it is based on a set of programmed parameters. A parametric model may appear disorganized, yet it is still defined by a set of parameters. Nonetheless, parametric design requires the use of programming logic to produce intricate designs (Reissmüller, J.J, 2015; Di Niccolo, F., 2016; Niclas, 2019). Additionally, the generation of design options can be done manually after the parametric model is created (Kilian, 2006). As in computer programming, a specific task can only be completed manually when a set of instructions are created by the corresponding code. Manual design generation can take longer and does not allow for optimization opportunities. Parametric design has its drawbacks, one of which is the time-consuming process of building the initial parametric model, which takes more time than traditional design methods. However, as the number of design options increases, the benefits of using parametric modeling become more apparent. Another limitation is that the design alternatives generated by a parametric model may share a common design concept and exhibit many similarities. Therefore, if the goal is to compare completely diverse design choices, parametric design may not be the best choice (Reissmüller, J.J, 2015; Yang, F., 2017). Eltaweel and Su (2017) claimed that parametric design software was initially created in 2008, but they did not provide any evidence to support this statement. They mentioned several tools that are commonly used for parametric design such as Catia, 3D MAX, 3D Maya, Revit, Grasshopper, Dynamo, Generative Components, Marionette, and Modelur. However, the authors did not explain the criteria they used to determine the popularity of these tools. Additionally, they stated that Grasshopper is the most widely used parametric design software, but they did not provide any data to support this claim (Reissmüller, J.J, 2015; Yang, F., 2017).

Designers have often adopted parametric modelling to get rid of repetitive tasks, shorten project time, rationalize designs, create free-form geometries, and optimize designs. Although it can be used with BIM, parametric modelling is primarily used for free-form geometries. As a result, there has been a surge in the development of novel computational methods and techniques aimed at streamlining the design process of intricate contemporary structures, and establishing an efficient quantitative link between the built environment and the building envelope, while taking into account the various hindrances that may impact the building design. Parametric design is a methodical approach that enables designers to generate numerous design solutions at the same time, in a highly efficient manner. Scholars Hernandez (2006) and Karle and Kelly (2011) agree that the ability to develop multiple design solutions in parallel is one of the most significant benefits of using parametric design (N. Gu et al., 2018).

In brief, parametric design is a rule-based, dynamic design process that uses constraints and variations to generate multiple design solutions concurrently. It excels in producing intricate shapes and optimizing various design solutions, which makes it a valuable tool for complicated building form generation and fabrication, structural and energy optimization, and other design prototyping tasks. As a novel digital design method, parametric design deviates from traditional CAD/CAM approaches in that it is characterized by algorithmic rules (N. Gu et al., 2018).

2.2.2 Potentials and Limitations of Parametric Modelling

Parametric modeling has become increasingly popular in recent years, and there are several reasons for its widespread adoption. Firstly, it allows designers to generate a vast number of design alternatives that can be analyzed and evaluated based on predefined criteria. Additionally, manipulating parameters can lead to the exploration of unexpected configurations, which can foster creativity and innovation. Another advantage of parametric modeling is that it increases interaction between the designer and the 3D model. This enhanced interaction enables the designer to visualize prompt variations on the 3D model and quickly evaluate them based on predetermined performance or aesthetic criteria, or even perform a relative comparison between instances. Furthermore, parametric modeling can facilitate interdisciplinary collaboration and complexity decomposition. The parameterization process, which defines the model structure, allows different disciplines to share in the setup of design strategies and subtasks. This approach highlights the hierarchical associations between geometries, leading to a more efficient and effective design process (Ahmed AbdelAziz, F.M.F., 2016; Niclas, 2019; Yang, F., 2017). Parametric design allows for a variety of analyses to be conducted simultaneously within a single model, leading to more comprehensive optimization. The system is advantageous not only for structural analysis, but also for building performance analysis, especially in terms of sustainability. Schlueter and Thesseling (2008) proposed and investigated "multi-parametric facade elements" using parametric design to explore their feasibility (N. Gu et al., 2018).

Parametric design has its drawbacks despite its advantages, there are a number of limitations. Firstly, creating the initial parametric model can be a time-consuming process and take longer than conventional methods. Furthermore, parametric design may lead to the generation of many design alternatives that share similarities and follow the same design concept. Therefore, if the goal is to compare and evaluate entirely different design options, parametric design may not be suitable. Hence, as designers face the need for higher levels of computation, they may encounter limitations. One way to overcome this is by reducing the number of parameters used in a partial model, which represents only some of the geometric entities. Another challenge arises when dealing with large solution spaces, where success in the parameterization process depends on selecting an appropriate range of solutions and a search mechanism that satisfies the performance criteria (Ahmed AbdelAziz, F.M.F., 2016; Yang, F., 2017).

2.2.3 Origins of Parametric Design

As depicted above in the previous paragraph, parametric design has gained widespread acceptance in various fields, including architecture, engineering, and product design. Although the term "parametric" originates from mathematics, its use in design is relatively recent. According to Davis D. (2013), a researcher at RMIT University who specializes in the technology of the building industry, completed his PhD on computational design and authored a thesis on the origins of parametric design entitled "A History of Parametric", where he highlighted that the origin of the term "parametric" in design cannot be traced to a single source. However, the concept of parametric design can be traced back to the early days of computer-aided design (CAD), where designers employed programming languages to automate design processes. The development of parametric modeling software such as Catia, 3D MAX, and Grasshopper has allowed designers to create intricate designs by manipulating parameters. With the capacity to generate a vast array of alternatives that can be evaluated based on predefined criteria, parametric design has become an essential tool in the design process (N. Gu et al., 2018; Eltaweel, A. & SU, Y., 2017; Toutou, A.M.Y., 2019). In 1978, Hillyard and Braid were created a system for designing mechanical components that could be considered a parametric approach, as it combined two parameters, such as dimensions and tolerances. However, the history of parametric design has been a subject of debate among scholars. While some argue that Luigi Moretti introduced the concept of parametric architecture in his book Writings of Architect in 1940 (Moretti, L. et al., 2000), Robert Stiles claimed that the concept had been around for much longer. In his paper On the Drawing of Figures of Crystals, James Dana discussed the use of parameters, variables, and ratios to draw a range of crystals as early as 1888 (Davis, D., 2013). Despite these debates, the development of parametric modeling software, such as Catia, 3D MAX, and Grasshopper, has enabled designers to create complex designs by manipulating parameters. Today, parametric design is widely used in various fields, including architecture, engineering, and product design, providing designers with the ability to generate a large set of alternatives that can be analyzed and evaluated based on predefined criteria (N. Gu et al., 2018; Eltaweel, A. & SU, Y., 2017).

In the late 20th century, there was a significant rise in the adoption of parametric design in architecture by both academic institutions and architectural firms. This was accompanied by the development and rapid evolution of software such as Generative Components™ (GC), Grasshopper, and Processing, which had advanced features. By the year 2000, the use of parametric techniques in building design had become more refined, and many landmark buildings using parametric design were proposed and constructed. Prominent architectural firms at the time, including Foster+Partners, Zaha Hadid Architects, UNStudio, KPF, AA Emtech, and SPAN, were leaders in utilizing parametric design. Designers had access to various parametric design tools to generate and manage free-form architectural designs. This was a significant milestone for many of these leading architectural firms that shifted their design process towards parametric modeling (N. Gu et al., 2018; Eltaweel, A. & SU, Y., 2017; Toutou, A.M.Y., 2019). Parametric design has gained significant traction in the field of architectural design over the last two decades, particularly among leading design practices. Some scholars have even proposed that it is a design style or movement that has supplanted Modernism (Schumacher 2009). At the 2008 Venice Biennale, Patrik Schumacher first introduced the term "parametricism," which he later elaborated on as a design philosophy that creates a new and intricate order based on the principles of differentiation and correlation (Schumacher 2009). The term has gained further attention at the 2011 ACADIA conference, where it became the central theme. It is possible for architects to utilize parametric modeling techniques to achieve varying degrees of complexity and design optimization while still maintaining modernist aesthetic principles in their buildings. This approach is demonstrated in projects such as Soho Shang Du in Beijing, which utilizes parametric tools to achieve a finely-tuned design, but ultimately presents a rather conventional appearance (N. Gu et al., 2018; Khelil, S., 2020).

2.2.4 The implementations of parametric design

Essentially, the term parametric is rooted in mathematics and denotes the utilization of particular parameters or variables that can be modified to influence the outcome of an equation (Frazer, J., 2016; Eltaweel, A. & SU, Y., 2017). Nowadays, parametric design is a versatile approach that is widely applied in various disciplines, where it involves complex algorithmic relationships, interdisciplinary collaboration, and innovative forms. In addition, it is also known for its ability to facilitate multi-processing treatments, which have led to significant improvements in design efficiency and accuracy across different fields including architecture, engineering, industrial and product design, and urban planning. Architects have found parametric design to be particularly useful in generating complex building geometries, facades, and structures. The availability of parametric tools has enabled architects to design intricate forms and shapes that would have been challenging or even impossible to create using traditional methods (Eltaweel, A. & SU, Y., 2017). The complexity of the operations involved in parametric design cannot be effectively managed through conventional tools or mental imagination alone, which is why the use of advanced operating systems, parametric tools, and specialized software is necessary. This technological advancement has led to the widespread application of parametric design across various fields, including but not limited to, interior design, fashion, architecture, urban planning, acoustics, structural analysis, and medicine which summarized in the following paragraph (Eltaweel, A. & SU, Y., 2017; N. Gu et al., 2018).

2.2.4.1 In the field of architecture

The introduction of parametric design has transformed the field of architecture by enabling the creation of innovative building designs with intricate geometries and forms that were previously challenging to construct using traditional design methods. Furthermore, parametric design allows architects to optimize building performance in critical areas such as energy efficiency and structural stability (Eltaweel, A. & SU, Y., 2017; N. Gu et al., 2018). Parametric design allows architects to generate a range of creative solutions to design problems by utilizing parameters to establish relationships between design elements. By using algorithmic methods, it enables exploration of multiple solutions to complex design challenges. Parametric design can also control sophisticated relations and establish a range of formal alternatives, providing architects with a wide range of options to choose from. This makes it an ideal tool for architects seeking to push boundaries and achieve innovative results in the design process (Hudson, R., 2010; Zarei, Y., 2012; Eltaweel, A. & SU, Y., 2017).

Several well-known architects have integrated parametric design into their work, including Zaha Hadid, Frank Gehry, and Santiago Calatrava (see Figure 2.3). The Beijing National Stadium, also known as the Bird's Nest, is an excellent example of parametric design in architecture, designed by Herzog & de Meuron and completed for the 2008 Olympic Games (see Figure 2.4).

Figure 2.3: Architectural models created based on parametric design
(Source: https://www.re-thinkingthefuture.com/2021/04/08/a3824-the-rise-of-parametric-architecture/)

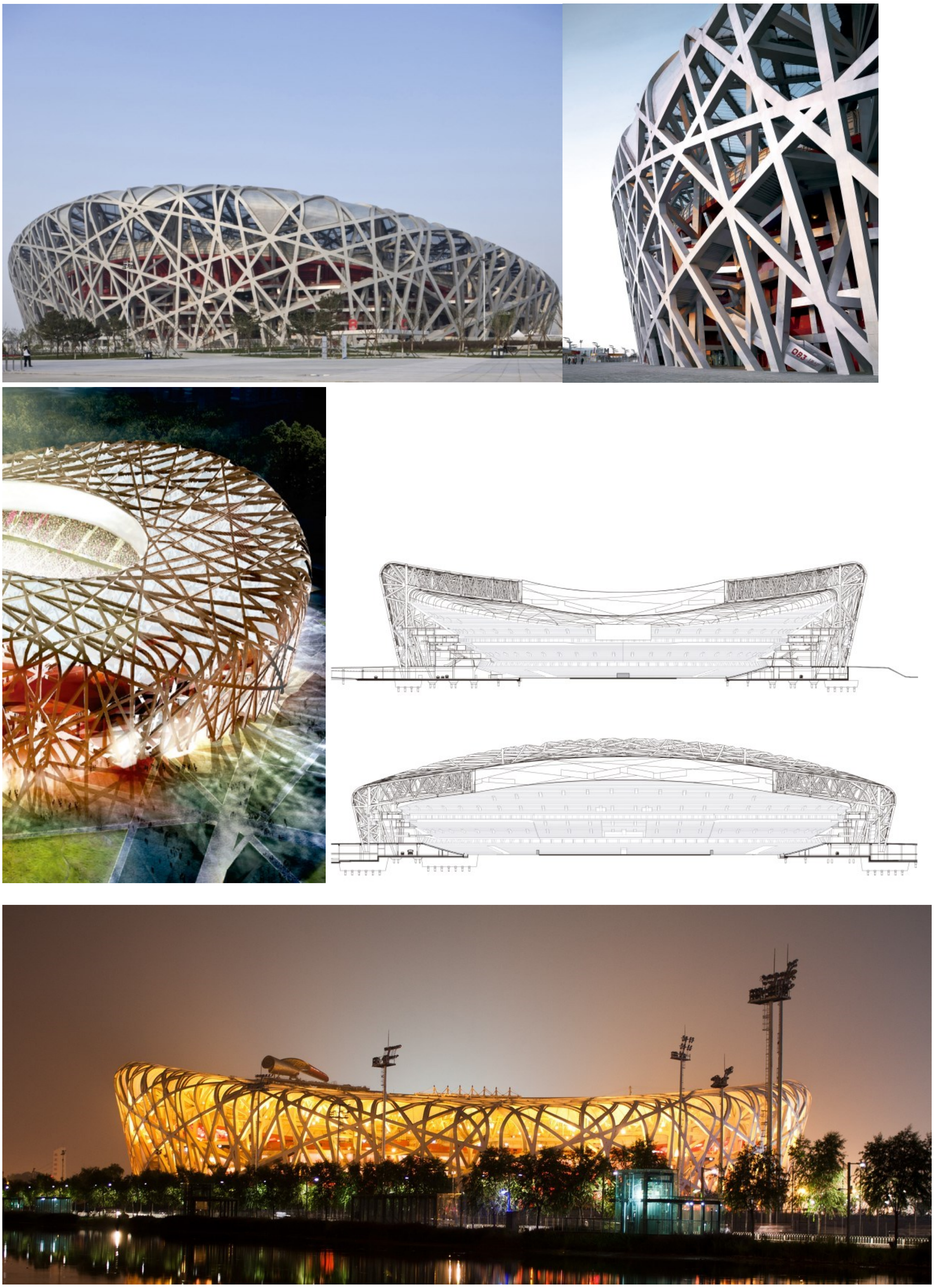


Figure 2.4: The Beijing National Stadium, the Bird's Nest
(Source: https://arquitecturaviva.com/works/estadio-nacional-en-pekin-6#lg=1&slide=13)

The stadium's intricate lattice structure was made possible through the use of parametric design tools. Parametric design has also been applied in the creation of innovative building facades, such as the Al Bahar Towers in Abu Dhabi (see Figure 2.5), which use responsive shading systems that adjust according to the sun's position throughout the day. Additionally, parametric design has been utilized to optimize structural design and construction processes, as seen in the works of firms such as Arup and Buro Happold (see Figure 2.6). As a whole, parametric design has broadened the possibilities for architects and designers, enabling them to extend the limits of what is feasible in building design and construction (Eltaweel, A. & SU, Y., 2017; Di Niccolo, F., 2016).

Figure 2.5: Al Bahar Towers in Abu Dhabi
(Source: https://www.archdaily.com/270592/al-bahar-towers-responsive-facade-aedas)

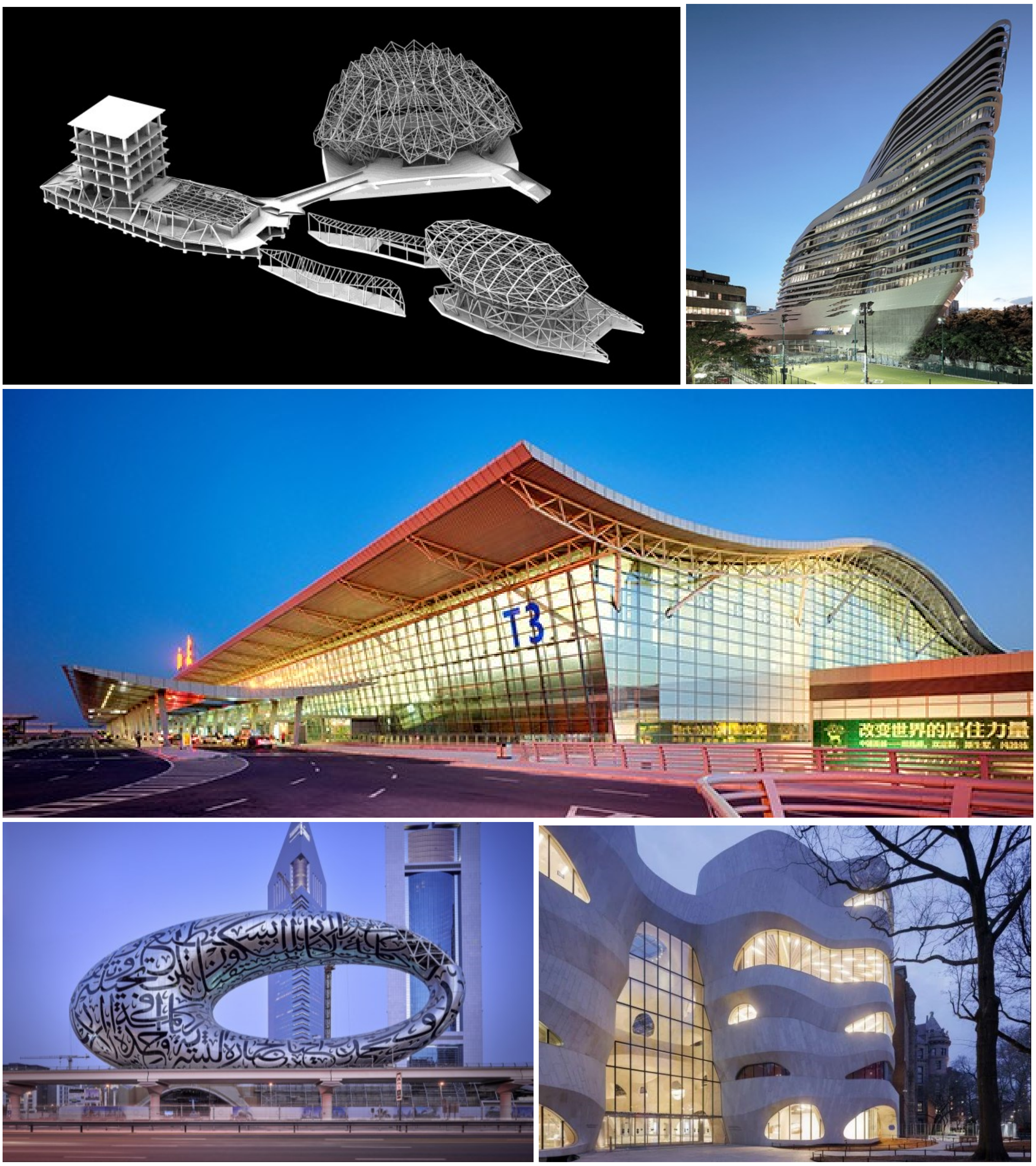


Figure 2.6: Examples of some projects of Arup and Buro Happold firm (Source: https://www.burohappold.com/articles/five-cultural-projects-to-look-out-for-in-2022/)

2.2.4.2 In urban planning

Parametric design has opened up new possibilities in the field of urban planning by enabling more efficient and precise decision-making processes. Urban planners can now generate and evaluate multiple design options and scenarios in a shorter amount of time using parametric modeling tools. This has been particularly useful in the development of transportation networks and infrastructure, where parametric modeling can be used to analyze traffic flow patterns and optimize design for maximum efficiency. Moreover, parametric design has proven valuable in the design of urban landscapes and public spaces. By analyzing factors such as sunlight, wind patterns, and pedestrian traffic using parametric tools, urban planners can create functional and aesthetically pleasing public spaces that cater to the needs of the community. Another application of parametric design in urban planning is the analysis and optimization of building density and placement. By considering factors like solar exposure, wind patterns, and proximity to public transportation, urban planners can create more sustainable and livable urban environments (Eltaweel, A. & SU, Y., 2017; Di Niccolo, F., 2016).

Parametric design has been increasingly used in urban planning to create more responsive and sustainable urban environments. One example in a previous study of Zhang, J. et al. (2019), the study was chosen a parametric design workflow for optimizing the performance of residential building design in Beijing, considering various factors such as energy consumption, indoor comfort, and cost-effectiveness. The approach involved the creation of a parametric model that allows for the exploration of various design alternatives and the evaluation of their performance using simulation and optimization tools. The results showed that the proposed approach can effectively improve the energy efficiency and indoor comfort of residential buildings while reducing costs. The study highlights the potential of parametric design in achieving sustainable and high-performance building design in the field of architecture and urban planning (see Figure 2.7).

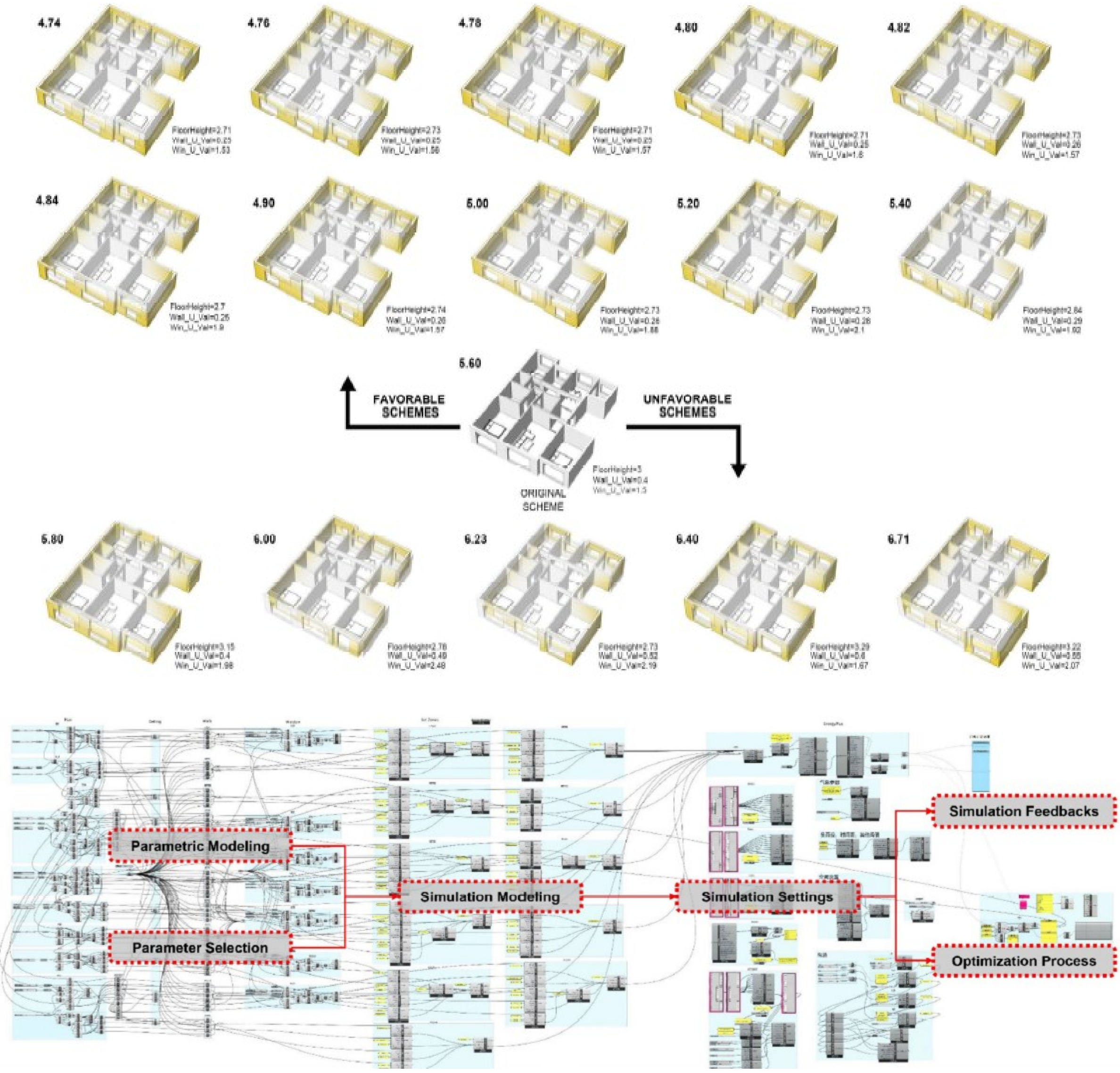


Figure 2.7: Parametric models in different building load grades (Source: Zhang, J. et al., 2019)

Another example in the same area, investigated by Mahaya, C. et al. (2022) in assessing the solar access of ten existing apartment building districts in Batna city of Algeria using parametric design in field of urban planning. The researchers developed a parametric model that takes into account several factors such as building orientation, distance between buildings, and shading devices. The model was used to generate different design alternatives that were evaluated based on their solar access performance. The findings from this study showed that the parametric approach can effectively optimize solar access in existing building districts, leading to more energy-efficient and sustainable urban environments. The study also highlights the potential of parametric design in urban planning and its ability to address complex design challenges related to environmental performance (see Figure 2.8).

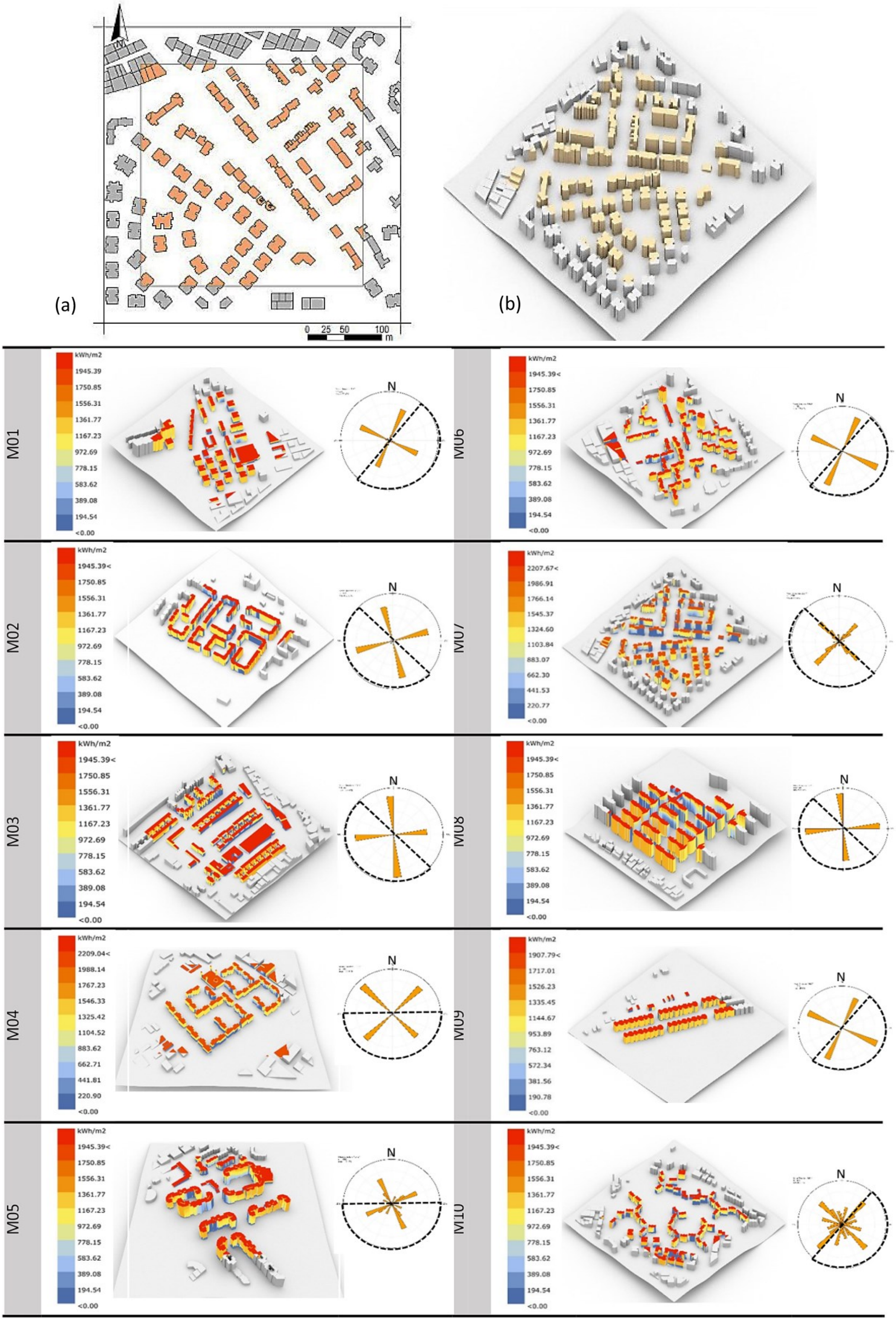


Figure 2.8: Grasshopper-Ladybug workflow used to construct 3D digital models, calculate morphological parameters, and perform solar simulations (Source: Mahaya, C. et al., 2022)

In summary, parametric design has the potential to transform the way urban planners approach design and decision-making, leading to more sustainable, efficient, and livable cities. Parametric design also offers a multitude of design possibilities that are difficult to achieve using conventional methods, and is especially useful in an iterative design process. Through its discrete problem-solving approach, parametric design can efficiently address multiple layers of complexity in urban design, saving time and improving coordination between these layers (Eltaweel, A. & SU, Y., 2017; Di Niccolo, F., 2016).

2.2.4.3 In environmental study

Parametric design has not been commonly utilized in environmental studies to analyze and optimize building and urban performance. Designers and researchers have mainly relied on conventional methods to evaluate the environmental impact of buildings and urban areas. These conventional methods involve complex simulations and manual calculations that are time-consuming and often inaccurate. However, some recent research has explored the potential of using parametric modeling tools in environmental studies. These studies have shown that parametric design can offer a more efficient and accurate approach to environmental analysis, allowing for the exploration of multiple design options and scenarios and the assessment of their impact on energy consumption, daylighting, and thermal comfort. It is possible to analyze and evaluate a variety of climatic and environmental factors such as the movement and intensity of the sun, humidity, radiation, wind speed, and heat gain, among others. Parametric design allows for the control and management of these factors in a systematic and precise manner. Furthermore, with the ability to simulate and model in the fourth dimension, time can also be incorporated into the design process to better understand how building performance may change over time. By using parametric tools to anticipate and address design challenges in the early stages of the design process, designers can create more efficient and effective buildings (Eltaweel, A. & SU, Y., 2017; Wagdy, A. et al., 2015; Banihashemi, S., et al., 2015). For instance, the study of Ahmed Toutou et al. (2019), explores the use of parametric design to optimize daylighting and energy performance in residential buildings located in hot arid zones. The study examines the potential of parametric design in optimizing building performance in hot arid zones. It proposes a framework that uses software tools to simulate and analyze various building parameters such as orientation, shading, glazing, and interior finishes. The study evaluates the framework's effectiveness in improving energy efficiency and daylighting performance of a residential building. The results indicate that the proposed framework is effective in optimizing building design to improve energy efficiency and daylighting performance. The study emphasizes the importance of using parametric design in creating sustainable and energy-efficient building designs in hot arid zones (see Figure 2.9).

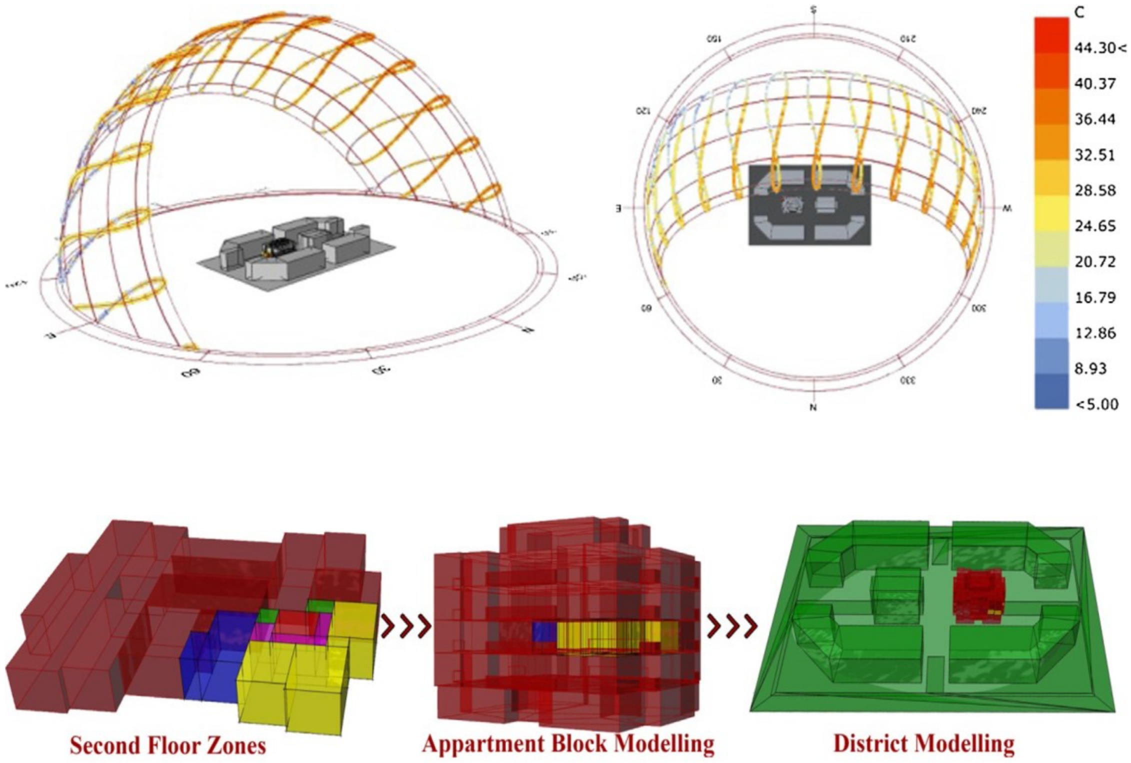


Figure 2.9: Examples for sun path and daylight performance analysis in Grasshopper (Source: Toutou, A., et al., 2019)

2.2.4.4 In industrial and product design

Parametric design has emerged as an increasingly popular approach in industrial and product design, facilitating the rapid and efficient generation of complex designs through computer algorithms and equations. This method enables designers to effortlessly explore various design options and variants, making it an indispensable tool across several fields, including automotive, architecture, furniture, product, and packaging design. In the automotive domain, parametric models can improve vehicle performance and aerodynamics. In architecture, parametric models can help create intricate and elaborate building designs. Furniture designers can create chairs and tables with customizable heights, angles, and shapes. Parametric models are also useful in product design, allowing designers to create intricate product designs like headphones, lamps, and smartphones. In addition, designers can use parametric models in packaging design to create tailored and cost-effective packaging solutions that fit various product shapes and sizes. In conclusion, parametric design has revolutionized the design process, enabling designers to create innovative designs efficiently, and has become a vital tool in industrial and product design (Eltaweel, A. & SU, Y., 2017; Visweswaran, 2020; Jeong, J., 2021; Tatjana Kandikjan, 2022). As seen in Figure 2.10, parametric design has found its way into numerous fields, from industrial design to fashion design and product design. Specifically in industrial design, parametric modeling has been utilized to highlight, portray, and adjust the essential geometric elements of product design.

Figure 2.10: Examples of parametric design in decoration and fashion
(Source: https://prointerior.info/en/futurizm-en/)

These elements encompass features like shape, pattern, structure, modules, and how they interrelate (Eltaweel, A. & SU, Y., 2017; Visweswaran, 2020; Jeong, J., 2021).

2.2.5 Parametric design Softwares

The PMO framework (Parametric modeling and optimization), which has evolved from the development of interconnected tools, is now recognized as the computational approach for creating conceptual structural designs through parametric modeling and optimization (Danhaive, R., 2015). Until now, only a few software packages have been designed and utilized for parametric design in practical applications. Although some software provides the flexibility of free-form modeling, designers can also develop rule algorithms using scripting plug-ins. This paragraph provides a brief introduction to a few of these software packages. While Rhino +

Grasshopper is frequently used for parametric design, particularly in architectural design, Digital Project (DP) and GenerativeComponents™ (GC) are more specialized for complex projects with large-scale parametric and geometric associations (N. Gu et al., 2018; Khelil, S., 2020; Niclas, 2019; Yang, F., 2017). Initially created by Dassault Aviation, a French aircraft manufacturer, in 1977, Computer Aided Three-dimensional Interactive Application (CATIA) has been utilized in various industries such as aerospace, automotive, and shipbuilding due to its capability in controlling and manipulating intricate geometries and its support for manufacturing accuracy. Numerous versions of CATIA have been developed over the years to improve its commercial applications, and it has gradually expanded its use to the field of architecture. With the aim of serving architectural design, Gehry Technologies developed Digital Project (DP) based on CATIA 5.0. DP is renowned for being an extremely powerful parametric software package capable of efficiently managing complex parametric and geometric associations, which makes it well-suited for large, intricate parametric design projects (N. Gu et al., 2018; Niclas, 2019; Yang, F., 2017). Then, Robert Aish developed GenerativeComponents™ (GC) for Bentley Systems in 2005. GC applies parametric concepts throughout the entire design process, from the initial conceptual phase to the final documentation. Moreover, GC has been combined with Building Information Modeling (BIM) and other analysis and simulation platforms to evaluate and optimize design. By integrating with these platforms, parametric design can become more specific and realistic, successfully connecting design concepts with production, fabrication, and construction processes. Thereafter, Eltaweel & Su (2017) and Khelil, S. (2020) conducted a review stating that parametric design software was initially introduced in 2008, with widely used tools such as Catia, Autodesk 3D MAX, Autodesk 3D Maya, Autodesk Revit, Archimatix, Grasshopper, Autodesk Dynamo, Generative Components, Marionette, Modelur and Rhinoceros 3D. Among these options, Grasshopper, a plugin for the NURBS modeling software Rhinoceros, is the most popular parametric design software available and commonly used for parametric design.

Rhinoceros + Grasshopper

Rhinoceros is a highly utilized 3D modeling software that employs NURBS (Non-Uniform Rational Basis Spline) technology. It finds extensive usage in academic settings, engineering firms, and architectural offices. Grasshopper, on the other hand, is an innovative plug-in for Rhinoceros that enables algorithmic modeling capabilities (Danhaive, R., 2015). Grasshopper 3D software (see Figure 2.11) is a versatile software with an open architecture that allows for the integration of various plugins. These plugins serve different purposes, ranging from building geometry development and structural analysis to environmental analysis and mechanical engineering. Notable building performance analysis plugins include Ladybug and Honeybee (Roudsari & Pak, 2016), Geco, Diva, and Archsim. These plugins establish a connection between parametric building models and building performance by employing energy modeling and simulation techniques. Similar to the conventional energy modeling process, these plugins require input data such as climate information, building geometry, material properties, occupancy schedules, HVAC descriptions, and operational details. The output typically includes energy consumption data, metrics related to thermal and visual comfort, as well as daylighting metrics (Niclas, 2019; Yang, F., 2017; Danhaive, R., 2015).

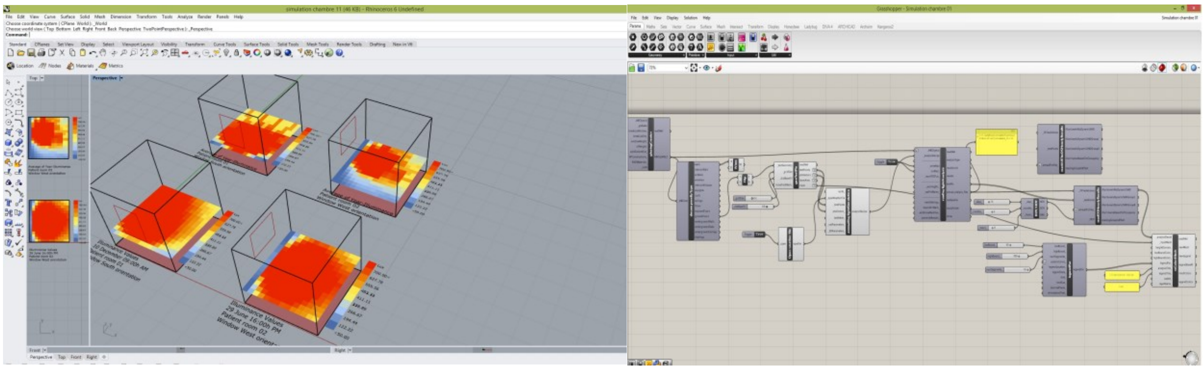
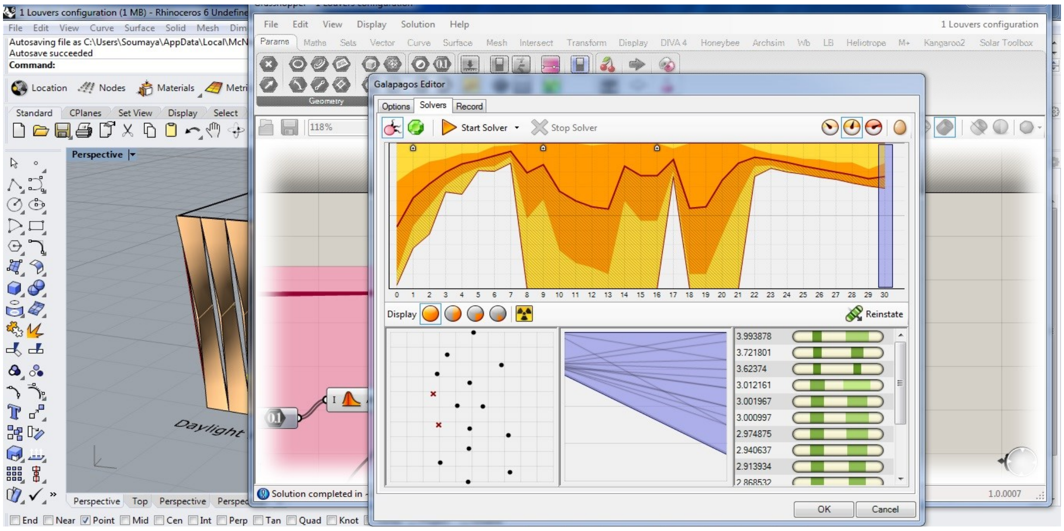


Figure 2.11: Grasshopper for Rhinoceros plugin interface (Source: Author, 2022)

Grasshopper offers an inherent set of problem-solving components known as Galapagos and Octopus, which are grounded in generative algorithms. These components are specifically designed for optimizing parametric design systems. Additionally, Grasshopper provides add-ons such as Ladybug and Honeybee, which enable daylight calculations. This comprehensive framework brings together all the necessary components within a single environment. Consequently, it has been extensively utilized in numerous research projects focused on parametric building design (Niclas, 2019; Danhaive, R., 2015). Galapagos and Octopus are two prominent plugins for Grasshopper, a visual programming tool for Rhino 3D modeling software.

Galapagos (see Figure 2.12) serves as an evolutionary solver plugin, utilizing genetic algorithms to optimize parametric designs. Drawing inspiration from Darwin's theory of natural selection, designers can define design variables, constraints, and objectives. Galapagos then undergoes an iterative process, exploring a range of design possibilities and continuously refining and evolving solutions across multiple generations. This approach aims to converge on outcomes that are either optimal or near-optimal (Niclas, 2019; Danhaive, R., 2015; Yang, F., 2017).



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2.974875
2.940637
2.913934
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Solution completed in

Figure 2.12: Galapagos plugin viewport (Source: Author, 2022)

In contrast, Octopus (see Figure 2.13) is a plugin designed for multi-objective optimization within Grasshopper. It equips designers with the ability to analyze and optimize parametric designs that involve multiple conflicting objectives. By leveraging sophisticated algorithms like NSGA-II (Non-dominated Sorting Genetic Algorithm II) and MOEA/D (Multi-objective Evolutionary Algorithm based on Decomposition), Octopus helps find solutions that strike a balance between various design criteria simultaneously.

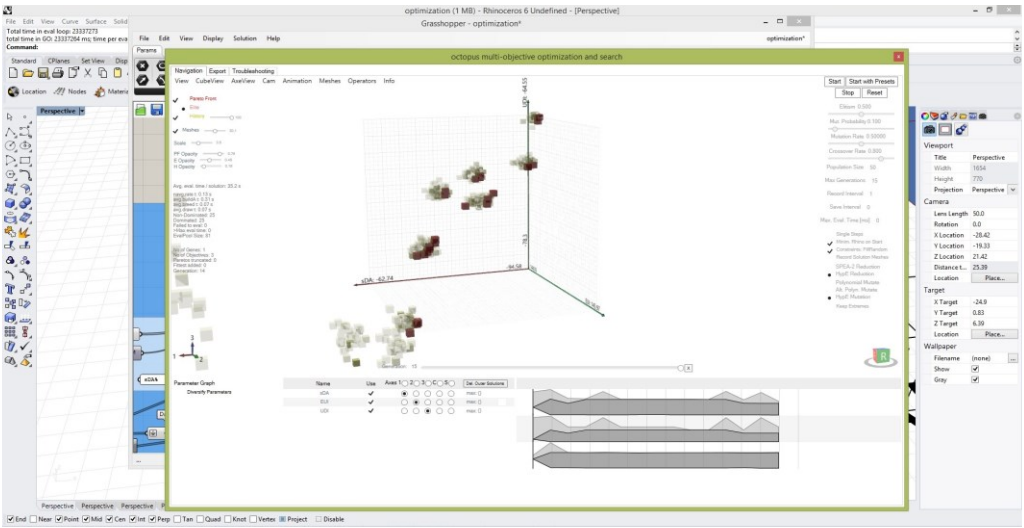


Figure 2.13: Octopus 3D viewport representing the objective space (Source: Author, 2022)

This enables designers to identify trade-offs and achieve Pareto-optimal solutions. Both Galapagos and Octopus plugins significantly enhance the capabilities of Grasshopper by providing powerful optimization tools specifically tailored for parametric design. Designers can leverage these plugins to explore and refine their designs based on specific objectives and constraints, ultimately achieving more sophisticated and efficient design outcomes (Niclas, 2019; Danhaive, R., 2015; Yang, F., 2017).

2.2.6 Parametric facades design

Parametric building facades encompass the application of parametric design principles and techniques in the development of building exteriors. Employing a parametric approach involves utilizing algorithms, rules, and parameters to manipulate and generate intricate geometries, resulting in facades that are adaptable, dynamic, and responsive to a variety of contextual factors and design objectives. Through parametric design, architects and designers gain the ability to craft elaborate and personalized facades capable of addressing environmental conditions, optimizing energy efficiency, managing daylighting, and enhancing visual aesthetics. By leveraging parametric tools and software, designers are empowered to explore an extensive array of design possibilities, iterate rapidly, and efficiently produce complex facade configurations that would be otherwise difficult to achieve using conventional design methods (Niclas, 2019; F. Hammad & B. Abu-Hijleh, 2010; J. M. L. Gagne and M. Andersen, 2010). As illustrated in the preceding section 3.2.5 (Parametric Design Software), the implementation of parametric building facades often entails leveraging advanced computational tools such as Grasshopper, Autodesk Dynamo, or other customized scripts. These tools enable the generation and manipulation of facade geometries based on specific design parameters. These parameters encompass a range of factors, including solar exposure, views, shading requirements, energy efficiency objectives, and aesthetic preferences. The utilization of parametric building facades can yield architecturally remarkable and highly functional solutions. Such facades possess the potential to significantly enhance both the appearance and performance of buildings. By creating dynamic and responsive structures, they seamlessly integrate with their environment and effectively fulfill diverse design goals (Niclas, 2019; F. Hammad & B. Abu-Hijleh, 2010; J. M. L. Gagne and M. Andersen, 2010).

Parametric systems have revolutionized the architectural design process by enabling designers to generate an extensive number of design iterations. By adjusting a set of parameters within a virtual environment, designers can explore numerous variations of a building design. However, considering the vast number of possibilities, manually investigating all options would be nearly impossible. This is where genetic algorithms prove valuable. Genetic algorithms provide a framework for searching for optimal solutions within an infinite space of generative possibilities, as described by W. H. Ko (2012). In this context, the parametric system functions as the genome, the range of possibilities represents the population, and the designer's objectives serve as the fitness function. Architects have extensively employed genetic algorithms, particularly in optimizing daylight systems. Genetic algorithms enable effective simulation of numerous potential outcomes, significantly enhancing the utility of parametric design in architecture. By leveraging these algorithms, designers can explore and analyze a broader range of possibilities, leading to more efficient and effective architectural solutions (Niclas, 2019; J. M. L. Gagne and M. Andersen, 2010).

In their research, S. Torres and Y. Sakamoto (2012), introduced a more intricate parametric design for a building facade. Their parametric approach involved 21 parameters, which collectively encoded the sizes, quantity, and positioning of windows. Through their experiments, they demonstrated that genetic algorithms offer a consistent and dependable method for optimizing this particular problem. The researchers observed consistency across multiple design runs, ensuring the attainment of an optimized solution rather than a local maximum. Though, one drawback of utilizing genetic algorithms is their computational intensity, as even a single generation may necessitate numerous simulations. To mitigate this issue, the researchers adopted specific strategies. They reduced computational burden by employing a subset of their meteorological data instead of the entire annual dataset. Additionally, they applied absolute elitism when selecting individuals for breeding in the subsequent generation. To avoid local maxima, three individuals were randomly chosen and included in the breeding group. This study strongly advocates for the utilization of genetic algorithms in the optimization of parametric building facades, as the test results validate its applicability. Furthermore, the paper discusses various optimization techniques for genetic algorithms that are crucial to consider in similar projects (Niclas, 2019).

In the realm of parametric building facades, the year 2020 witnessed notable advancements as researchers and practitioners delved deeper into the possibilities offered by parametric design principles for the development of inventive and eco-friendly building exteriors. A particular area of interest was the emergence of adaptive facades, which garnered considerable attention. Researchers directed their efforts towards exploring how parametric design principles could be effectively utilized to fashion facades capable of dynamically adapting to fluctuating environmental conditions. These adaptive facades could seamlessly adjust their characteristics, such as transparency, shading, and ventilation, to optimize both occupant comfort and energy efficiency (Niclas, 2019; Jeong, J., Park, 2021).

2.2.7 Parametric façade design and daylighting

In this review of the literature, the focus will be on exploring the role of parametric design in relation to daylight. As previously discussed, the utilization of parametric design offers a means to tackle and manipulate intricate relationships based on the availability of interconnected data. Any modification made to a given parameter has a significant impact on the entirety of the data. Daylight holds considerable importance in our daily lives, particularly when it comes to architectural considerations such as design concepts, facades, forms, functions, orientation, and even materials. Daylight is influenced by a multitude of diverse factors including longitude, latitude, sun-path, solstice, equinox, sky type, wind speed, solar radiation, humidity, and geographical location. Each of these aspects comprises distinct parameters that are interconnected and mutually influenced. Parametric design offers a valuable tool for connecting and integrating these data points through specialized software, thereby facilitating design decisions, modeling processes, and problem-solving activities. Moreover, it has the potential to anticipate optimal solutions for building design, particularly through the analysis of daylight influence (Eltaweel & Su, 2017).

As the architectural geometry is established according to predefined rules, the incorporation of evolutionary multi-objective algorithms (Caldas, L., 2008), (L.G. Caldas, L.K. Norford, 2008) becomes crucial in order to harmonize and optimize various facets involved, ultimately leading to the creation of an optimized facade element. Over the past years, numerous approaches have emerged and been implemented in buildings, utilizing Genetic Algorithms (GA) to minimize overall energy consumption based on factors such as dimensions, shapes, orientation, and window-to-wall ratio (WWR) [13,14], or to determine the most favorable facade solutions (G. Zemella & A. Faraguna, 2014; D. Tuhus-Dubrow & M. Krarti., 2010). While there have been several instances of these applications on a building scale, research specifically focusing on the genetic optimization of shading devices remains scarce. Notably, Omidfar, A., (2011) conducted a study employing GA to optimize shading device geometry based on daylight indexes (Andrea, Z. et al., 2016; Eltaweel & Su, 2017).

2.2.7.1 The application of louvers configuration

For instance, in a previous study of Wagdy, A. and F. Fathy (2015), an extensive exploration of various screen configurations for daylighting was conducted, focusing on the design of louvers. The investigation employed a parametric approach, utilizing a parallel computing algorithm to comprehend the influence of different louver parameters and their interactions on daylighting performance. These parameters included the number of louvers, the depth ratio of the louvers, the tilt angle, the window to wall ratio, and the reflectivity. Through parametric connections, a comprehensive set of 1600 configurations was generated, organized into 200 distinct groups, as depicted in Figure 2.14. The simulation process was carried out in parallel using Grasshopper and Radiance, seamlessly linked via an algorithm called Diva. Diva facilitated the integration of Radiance and EnergyPlus interface engines (Henriques, G.C. et al., 2012) for a comprehensive analysis (Wagdy, A. & F. Fathy, 2015; Henriques, G.C. et al., 2012; Eltaweel & Su, 2017).

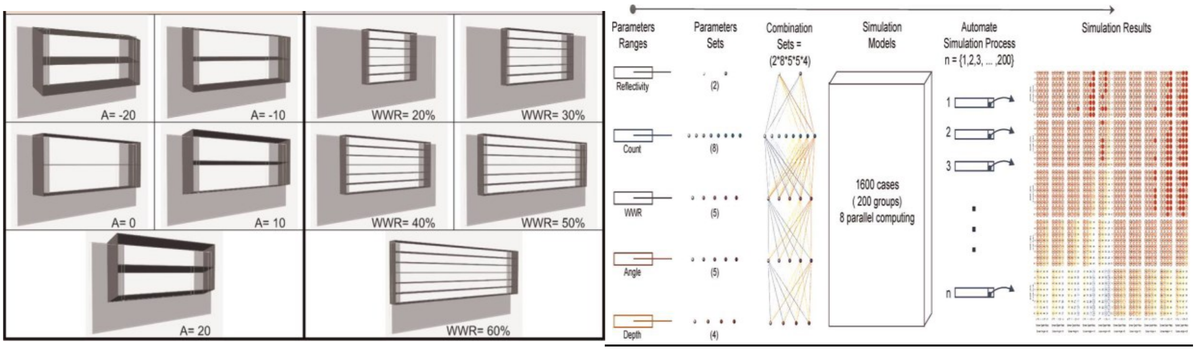


Figure 2.14: Louvers configuration with parametric algorithm for computing all possible combinations (Source: Wagdy, A. & F. Fathy, 2015)

Sherif, A. et al., (2015) also investigated in louvers (see Figure 2.15), through a comprehensive approach that involved a combination of analytical methods and simulations, the researchers examined the effects of various window configurations on daylight penetration in the ICU. Additionally, they conducted an assessment of the ICU's energy performance, considering both lighting and cooling requirements, while accounting for the specific climatic conditions prevalent in the desert region. The ultimate goal of the study was to offer valuable insights and recommendations for the optimal design of ICU windows. The aim was to achieve an ideal balance between maximizing daylighting and minimizing energy consumption. These research findings have the potential to significantly contribute to the development of sustainable and efficient hospital designs, particularly in desert climates, where both patient well-being and operational costs depend on effective daylighting and energy efficiency (Sherif, A. et al., 2015).

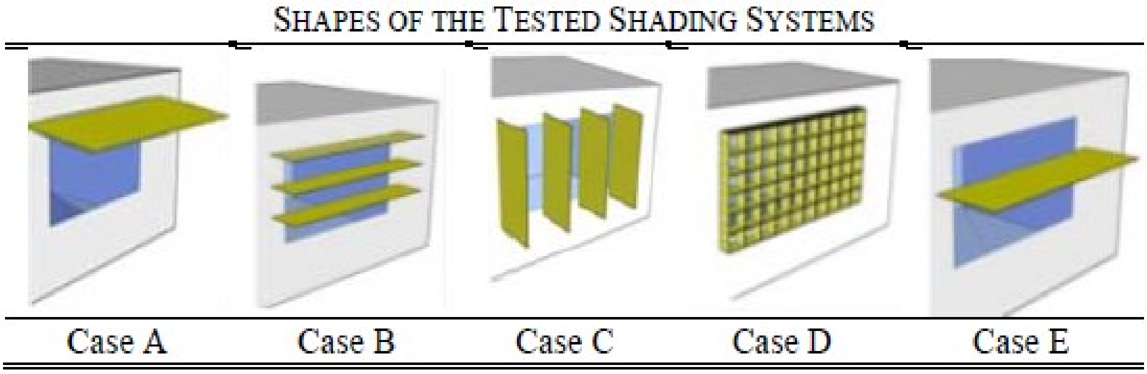


Figure 2.15: The configuration of shading systems (Source: Sherif, A. et al., 2015)

Another study conducted by Wagdy, A. et al., (2017) in the same area topic, toward employing advanced simulation techniques, this study comprehensively evaluates various designs of sun-breakers to assess their impact on daylighting conditions within hospital patient rooms. The primary objective is to analyze how different configurations of sun-breakers affect the levels of natural light, with a specific focus on minimizing glare and heat gain. The outcomes of this research offer significant contributions to the field of designing and positioning external sun-breakers for south-oriented windows in patient rooms of hospitals located in desert regions. The findings provide crucial insights that can be leveraged to optimize the arrangement of sun-breakers, achieving a harmonious equilibrium between adequate daylighting for patient well-being and effective reduction of heat and glare (Wagdy, A. et al., 2017).

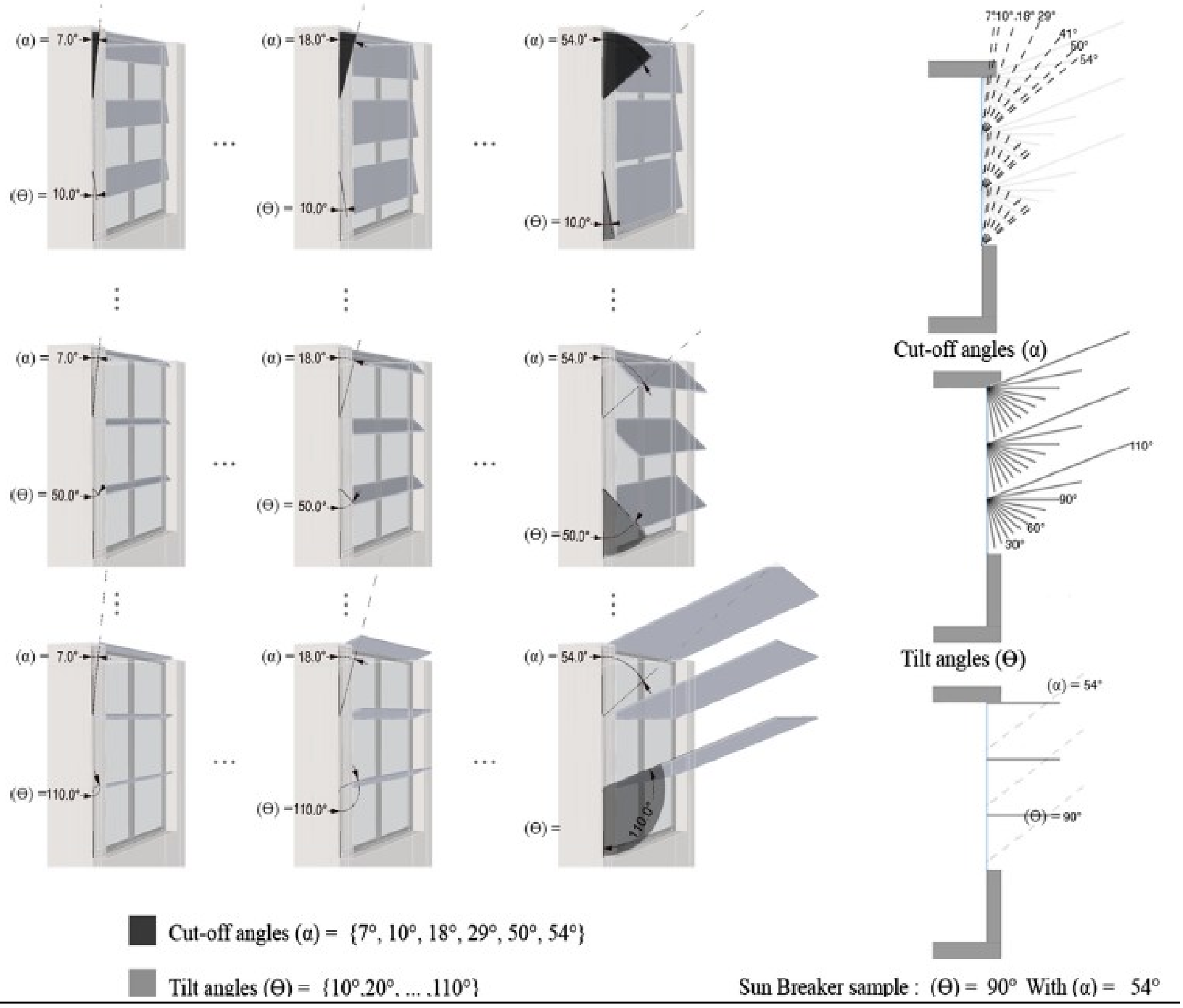


Figure 2.16: Cross section in the window illustrating the tested tilt angles (h), cut off angles (a), and the resultant sun-breaker shapes (Source: Wagdy, A. et al., 2017)

2.2.7.2 Fenestration configuration

Fenestration parametric design encompasses a methodology that relies on adjustable parameters to shape and optimize the design of windows and other building openings. This approach allows for a methodical exploration of diverse design possibilities by manipulating variables such as window dimensions, forms, orientations, and glazing attributes. The core objective of fenestration parametric design centers on enhancing the performance of natural daylight within buildings. Daylight performance involves effectively utilizing sunlight to illuminate interior spaces, thereby reducing reliance on artificial lighting and fostering environments that are visually pleasing, energy-efficient, and conducive to human comfort. With implementing fenestration parametric design, architects and designers can scrutinize the impact of various window configurations on factors like daylight levels, light distribution, glare mitigation, and energy consumption. Through iterative simulations and assessments, they can refine the fenestration design to optimize daylight penetration while minimizing concerns such as glare and unwanted heat gain.

This approach offers numerous advantages, such as the flexibility to tailor fenestration designs to specific building contexts, climate conditions, and user preferences. It also enables designers to account for elements like solar heat gain, shading devices, and daylight harvesting systems during their parametric investigations. In essence, fenestration parametric design assumes a pivotal role in realizing sustainable and comfortable built environments by effectively integrating daylight as a primary design consideration and harmonizing it with other performance criteria (Dubois, M., 2001; Eltaweel & Su, 2017).

Lauridsen, P.K.B. and S. Petersen, (2014) conducted a study on parametric approach utilizing Grasshopper to produce various fenestration systems for a room that meets specific performance criteria encompassing indoor climate, daylighting, and energy conservation (see Figure 2.17). Within this method, a novel Grasshopper plugin called ICEbear was employed, enabling the simulation of annual indoor climate, daylighting, and energy performance for intricate geometries using hourly weather data. Simultaneously, the Galapagos optimization algorithm was employed in conjunction with ICEbear to generate design solutions based on the designer's conceptual ideas. The objective of this approach was to achieve optimal energy utilization for building operation (25 kWh/m^2/year), while simultaneously meeting the requirements of thermal class II (with fewer than 100 hours above 26°C) and attaining a minimum daylight autonomy of 60% at a specific location within the room (Lauridsen, P.K.B. & S. Petersen, 2014; Eltaweel & Su, 2017).

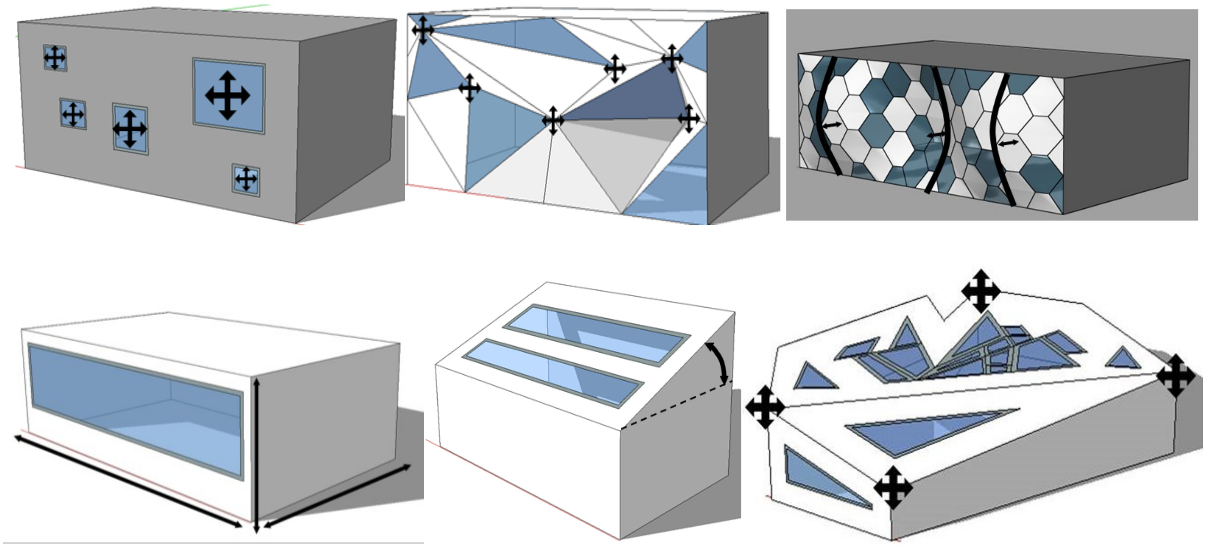


Figure 2.17: Examples of parametric models concepts and variables
(Source: Lauridsen, P.K.B. & S. Petersen, 2014)

For the same issue, Hassan, A. et al. (2017) investigated in using generative algorithms to explore design alternatives for the fenestration system of a building (Refer to Figure 2.18).

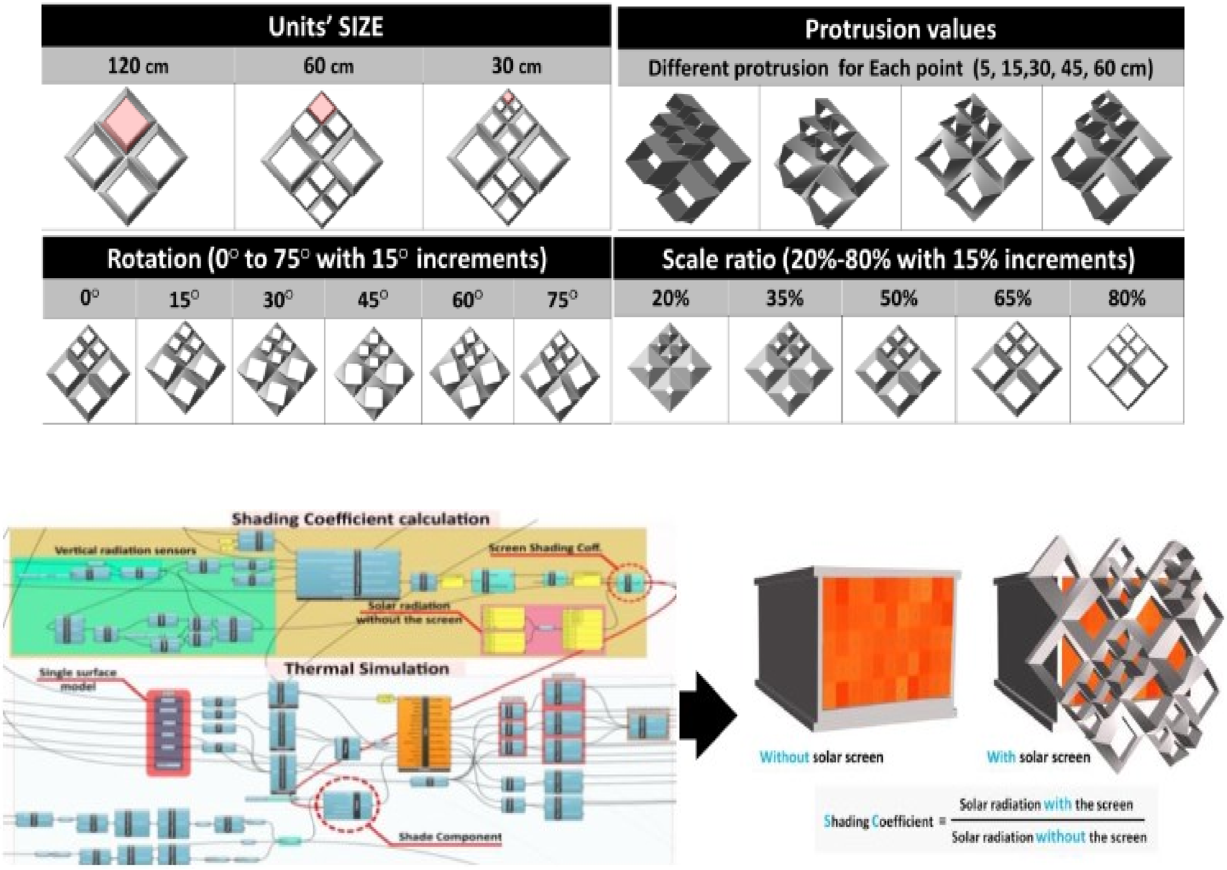


Figure 2.18: The screen parameters configuration (size, rotation, scale, protrusion)
(Source: Hassan, A. et al., 2017)

The study aimed to compare the effectiveness of parametric simulations and Genetic Algorithms in optimizing non-conventional solar screens on south-facing facades, with a focus on daylight, thermal, and energy performance. The specific focus of this paper is on the parametric simulation study of a non-conventional solar screen driven by both daylight and thermal considerations. The simulations were conducted on the facade of a south-oriented office space in Cairo, Egypt. The solar screen's various parameters, including sizes, rotation angles, scale ratios, and protrusion values, were modeled parametrically to align with the specific facade. The findings of this research provide insights into the design and optimization of non-conventional solar screens in hot arid climates. The results can be utilized to inform architects and designers about effective strategies for achieving a balance between daylighting and thermal performance, contributing to the development of sustainable and energy-efficient building facades in these specific climatic conditions (Hassan, A. et al., 2017).

2.2.7.3 The application of skylight configuration

The integration of skylight parametric systems with a daylight performance study aims to investigate and refine the design of skylights, optimizing their ability to enhance daylighting within buildings. Skylights, also known as roof windows, facilitate the entry of natural light into indoor spaces, reducing reliance on artificial lighting and establishing a visually pleasing atmosphere. Through the utilization of parametric design techniques, architects and designers have the capacity to manipulate various factors associated with skylights, such as dimensions, forms, orientations, glazing characteristics, and shading mechanisms. By adjusting these factors and employing simulations, they can evaluate and gauge the influence of different skylight arrangements on aspects like daylight levels, light distribution, control of glare, and energy consumption. The daylight performance study centers on evaluating the efficacy of skylight parametric systems in providing adequate and uniform natural light throughout the day. This evaluation may involve the measurement and analysis of parameters such as illuminance levels, daylight factor, sky component, and spatial daylight autonomy. Such metrics yield valuable insights into the quality and quantity of available daylight within interior spaces, allowing for well-informed design choices. The ultimate objective of this approach is to optimize skylight design in order to maximize the penetration of natural light while minimizing potential drawbacks like glare and excessive heat accumulation. Through iteratively adjusting and analyzing parametric variations, designers can discern the most effective skylight configurations that fulfill specific performance criteria and address user needs (Eltaweel & Su, 2017).

Xue, Y. & Liu, W (2023) conducted a study the optimization of atrium daylight and energy performance through skylight and shading design in commercial buildings in cold zones. Following the dynamic simulation of daylight and energy consumption, an analysis was conducted to assess the sensitivity of skylight and shading (SAS) design parameters across three different shading types. Subsequently, a multi-objective search tool was utilized to obtain the Pareto front solution set, optimizing commercial atriums for daylighting, visual comfort, and energy performance based on the three shading types. The findings revealed that the shading reduction ratio (SRR) exhibited the most significant influence on spatial daylight autonomy (sDA), daylight glare probability (DGP), and energy use intensity (EUI) across all shading scenarios. In contrast, the solar gain coefficient (SGT) had a greater impact on EUI compared to daylight quality. Additionally, the fabric coefficient (FC) had a more pronounced effect on EUI than the visual factor (FV), while the lighting system (LS) and lighting intensity (LI) had substantial influences on daylighting and visual comfort. Through screening, the optimal SAS values were determined for three shading options: no shading, fabric shading, and louvered shading. For no shading, the recommended values were SRR of 0.4–0.5 and SGT of Double silver Low-E insulating glass. Fabric shading called for SRR of 0.5–0.6, SGT of Double silver Low-E insulating glass, FV of 0.5–0.7, and FC of 0.5–0.6. Lastly, louvered shading suggested SRR of 0.6–0.7, SGT of Double silver Low-E insulating glass, LS of 100 mm/125 mm, and LI of 60–70 degrees (Xue, Y. & Liu, W., 2023).

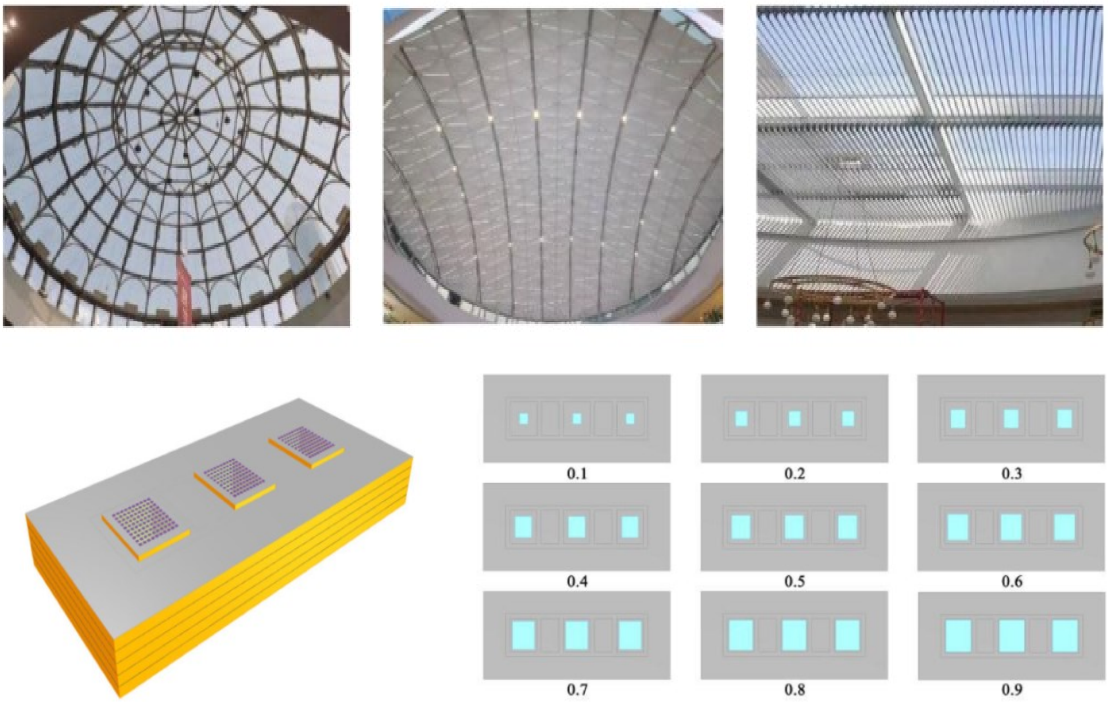


Figure 2.19: Commercial atrium skylight shading types (Source: Xue, Y. & Liu, W., 2023)

Other research conducted by Mohamed Marzouk (2020), explores the potential impact of introducing a light redirecting control element on daylight performance, focusing specifically on an Egyptian heritage palace skylight. The study aims to investigate the effects of integrating a light redirecting control element, such as a light shelf or light redirecting film, into the skylight design. These elements are intended to enhance the distribution and redirection of daylight, ultimately improving the overall daylighting performance within the heritage palace. To evaluate the daylighting performance, a combination of measurements and simulations is employed, comparing the skylight's performance with and without the light redirecting control element. Various parameters are considered in the analysis, including illuminance levels, distribution of daylight, and the potential to control glare. The research findings shed light on the effectiveness of the light redirecting control element in enhancing the daylighting performance of the Egyptian heritage palace skylight. This study contributes to a deeper understanding of how such elements can optimize daylight utilization in historical buildings, where the preservation of cultural heritage and ensuring occupant comfort are key priorities (Marzouk, M. et al., 2020).

In the study of Patric, Paul, and Kera (2014), proposed several design options for an atrium located at the University of Massachusetts in Lowell. Their objective was to effectively illuminate the building floors and bring natural daylight deep into the interior spaces. To achieve this, they employed a parametric approach in the design process, utilizing tools like Diva for Rhino and Grasshopper. The methodology of the study revolved around exploring the use of reflective systems to harness daylight and distribute it across the building's interior surfaces. To analyze and understand the effectiveness of various techniques used in different buildings, the researchers examined multiple system approaches, as illustrated in Figure 2.20. This allowed them to identify strategies that could maximize the utilization of daylight within the atrium and enhance the overall lighting conditions throughout the building (Patric, Paul, and Kera, 2014).

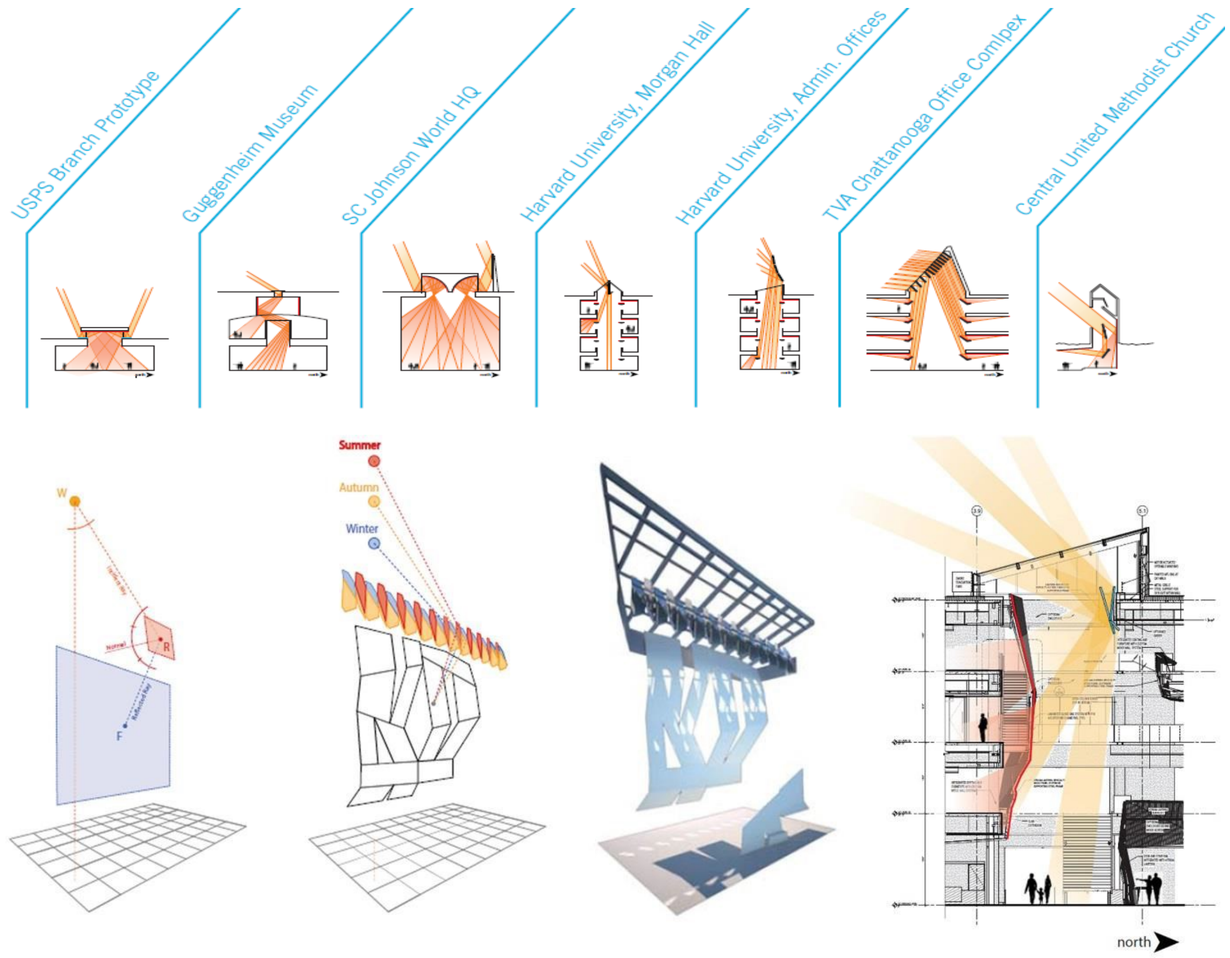


Figure 2.20: Daylighting redirecting strategies at University Crossing (Source: Patric, Paul, and Kera, 2014)

In summary, the integration of skylight parametric systems within a daylight performance study offers a systematic and data-driven methodology for the design and optimization of skylights. This approach ultimately leads to improved daylighting conditions, enhanced visual comfort, and the potential for energy savings within buildings.

2.2.7.4 Automated shading system configuration

Parametric daylight performance evaluation in conjunction with automated shading system configuration involves utilizing parametric design techniques to optimize the performance of automated shading systems in buildings, specifically focusing on daylighting. Architects and designers can utilize parametric design methods to manipulate various parameters associated with the shading system, including size, shape, orientation, and control strategies. Through iterative adjustments of these parameters, they can explore different configurations and assess their impact on daylight levels, light distribution, glare mitigation, and energy consumption. The primary objective of this approach is to determine the most efficient shading system configuration that maximizes the utilization of natural daylight while minimizing potential issues such as glare and excessive heat. By conducting simulations and evaluating performance metrics, designers can analyze the daylighting performance of different shading system configurations and make well-informed design choices. Automated shading systems offer the advantage of adaptability by dynamically responding to external factors like sun position and cloud cover. Integrating parametric design with automated shading systems allows designers to create responsive solutions that optimize daylight penetration throughout the day and across different seasons (Eltaweel & Su, 2017).

Daylight optimization was investigated by Tabadkani, A. et al. (2018), the research aims to examine the functionality of sun responsive skins concerning daylighting and visual comfort. Sun responsive skins are specifically devised to adapt dynamically to solar conditions, ensuring appropriate shading and fostering an optimal interior daylighting environment. As seen in Figure 2.21 towards implementing parametric design techniques, the study investigates a range of parameters related to sun responsive skins, including dimensions, forms, orientations, and material characteristics. Through a series of iterative simulations and evaluations, the influence of these parameters on daylighting and visual comfort is scrutinized. The research findings showed valuable insights into the efficacy of oriental sun responsive skins in optimizing daylighting conditions and augmenting visual comfort. The application of parametric analysis allows for an exhaustive exploration of diverse design possibilities, enabling the identification of the most suitable configurations that align with the desired objectives of daylighting and visual comfort (Tabadkani, A. et al., 2018).

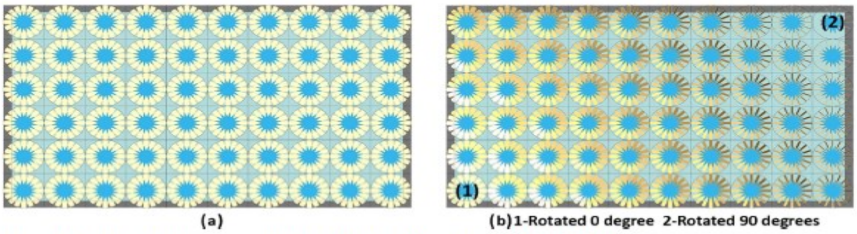


Fig. 6 (a) Rosette modules before being responsive; (b) rotation of Rosette modules (0–90 degrees)

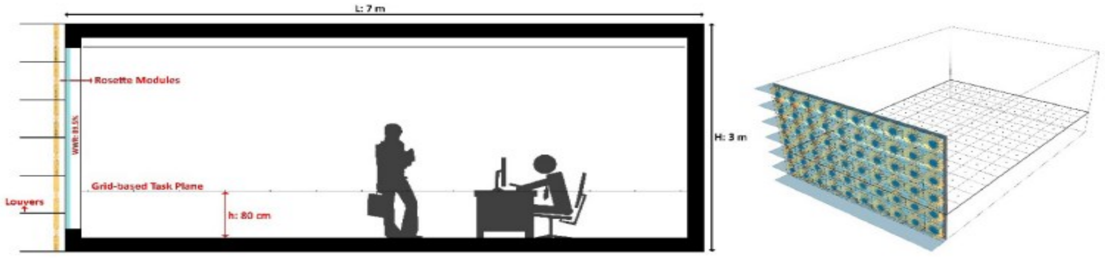


Figure 2.21: Skin configuration and grid-based task area (Source: Tabadkani, A. et al., 2018)

A study conducted by Y. Elghazi, A. Wagdy, S. Mohamed, and A. Hassan (2014), explored daylight optimization in a residential facade in Cairo using the Kaleidocycle design technique inspired by Origami. The objective was to improve daylighting in a living room and meet the requirements of LEED V4 (2014).The research methodology focused on utilizing the parameters of the Kaleidocycle logic (see Figure 2.22). Parametric design techniques were applied using software tools such as Rhinoceros, Grasshopper, and Diva. Diva, which integrates with Radiance and Daysim , was employed as an engine for conducting simulations. By employing the Kaleidocycle design technique and parametric analysis, the study aimed to enhance daylighting conditions in the living room of the residential facade. The use of Rhinoceros, Grasshopper, and Diva enabled the exploration of various design options and the evaluation of their impact on daylight performance. The study's outcomes provide insights into the effectiveness of the Kaleidocycle design technique and parametric design in optimizing daylighting and meeting LEED V4 requirements in residential settings. The research contributes to advancing knowledge in the field of daylight optimization and offers potential strategies for achieving sustainable and well-lit living environments (Y. Elghazi, et al., 2014).

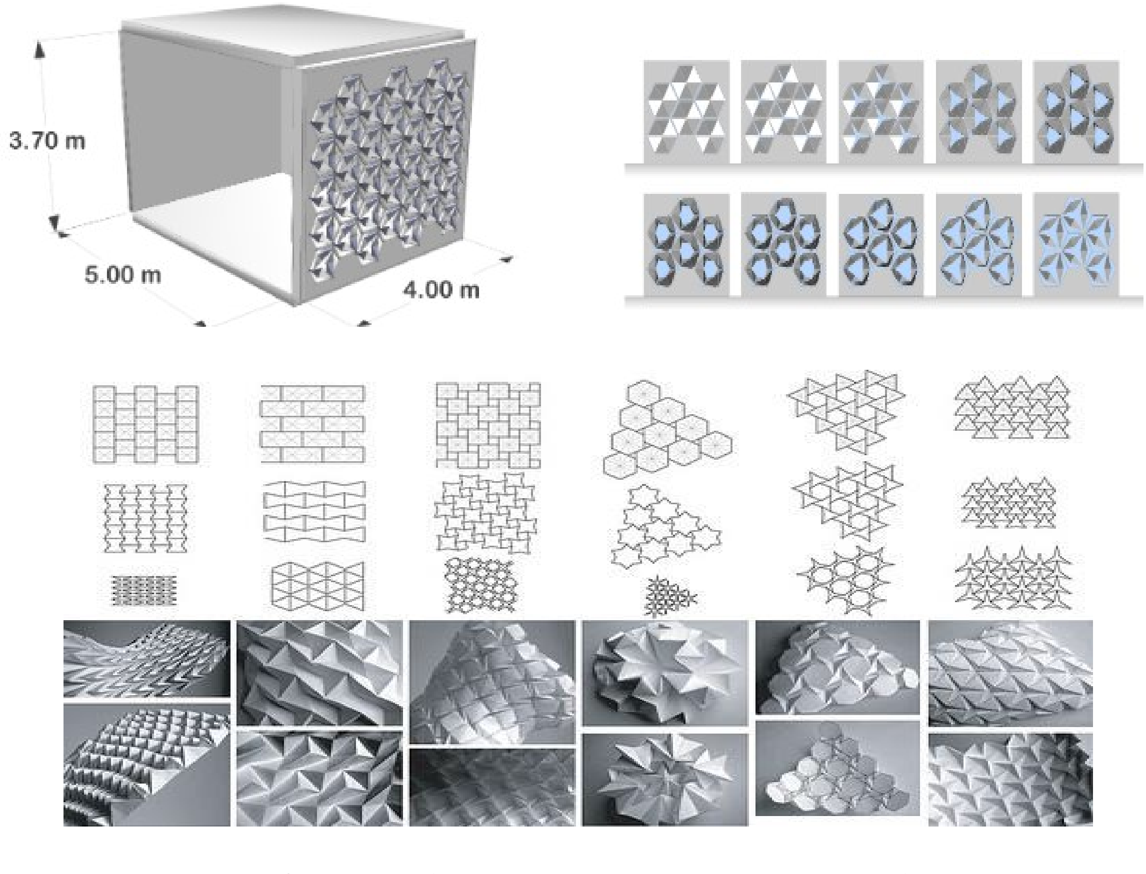


Figure 2.22: Origami forms based on geometrical rules (Source: Y. Elghazi, et al., 2014)

2.3 Building Performance Optimization and Evolutionary algorithms

2.3.1 Optimization for building design problems

In response to the increasing demand for energy-efficient buildings, there has been a proliferation of building energy simulation tools. These tools have played a significant role in the implementation of green building standards like LEED in worldwide. Designers, engineers, and developers have increasingly embraced sustainable and energy-saving design approaches. Building simulations have found applications in various areas, including calculating heating and cooling loads, assessing daylighting performance, analyzing reflective roof options, designing energy management and control systems, ensuring compliance with building regulations, conducting code checks, performing cost analyses, and more (Hong et al., 2000). Despite the availability of numerous simulation tools, the optimization process, which typically involves iterative simulations, remains inefficient and time-consuming (Yang, F., 2017; Su, Z., & Yan, W., 2015).

Evolutionary algorithms belong to a category of heuristic search methods widely utilized for optimization purposes. GAs are designed to generate improved solutions by iteratively evolving populations of potential solutions. This adaptability makes GAs highly flexible and allows for user interactivity. It is important to note that due to their stochastic nature, GAs do not guarantee finding the global optimum solution and operate with populations of solutions rather than a single solution. Moreover, GAs are easily customizable as they only require an objective or fitness function and encoded parameter representations. This makes them applicable to a wide range of problems, as long as performance parameters can be clearly defined (Danhaive., R., 2015 ; Yang, F., 2017).

Optimization, as defined by Merriam Webster Online (2017), refers to the process or methodology of maximizing the functionality or effectiveness of a design or decision. From a mathematical perspective, optimization involves finding the minimum or maximum value of a function by identifying the optimal values for the variables involved. Optimization allows for the efficient exploration of a wide range of design solutions, although the translation of a building design problem into a mathematical framework can be challenging. In recent years, advancements in parametric design, building performance simulation, and optimization technologies have made it feasible to optimize building performance. While the use of mathematical optimization in building performance began in the 1980s and 1990s, the majority of studies focusing on building performance optimization with building energy simulation and algorithmic optimization engines were published in the late 2000s (Nguyen, Reiter, & Rigo, 2014). These developments have paved the way for enhanced understanding and improvement of building performance through systematic optimization processes (Yang, F., 2017). The process of optimization typically involves the utilization of two main components: variables and objective functions. In the context of building performance optimization, variables represent the adjustable values that govern the geometry or characteristics of the design, while objective functions encompass the performance metrics associated with the building, often computed through simulation tools (Machairas, Tsangrassoulis, & Axarli, 2014; Yang, F., 2017). Optimization studies in building performance often focus on investigating various design variables, including but not limited to the building's orientation, shape, dimensions of construction, materials used, window-to-wall ratio, lighting fixtures, and sizes of HVAC systems. Towards the consideration of these design variables, researchers seek to identify the most optimal configurations that lead to improved building performance and meet specific performance objectives (Yang, F., 2017).

In a conventional optimization process, specialized algorithms are employed to identify the minimum or maximum values of a given function. This function, referred to as the objective function, can be influenced by numerous parameters, and any feasible combination of parameter values within the designated search space is considered a valid solution. The optimal solution is determined by identifying the set of parameters that minimizes (or maximizes) the objective function. It's important to note that a problem does not necessarily have a unique solution. It can have no optimal solutions, a finite number of solutions, or even an infinite number of solutions, which may be defined as a more specific subset within the search space (Papalambros and Wilde 2000; Gadelhak, M. I. A., 2019).

2.3.2 Multi-Objective Optimization

Multi-objective optimization is a field of study that addresses problems characterized by the presence of multiple conflicting objectives (Gadelhak, M. I. A., 2019). These objectives can encompass a range of factors, such as cost, performance, efficiency, and sustainability. The aim of multi-objective optimization is to find a set of solutions that offer a trade-off between these objectives, rather than a single optimal solution. Through the consideration of multiple objectives simultaneously, decision-makers can gain a deeper understanding of the trade-offs involved and make informed decisions that align with their priorities and constraints.

In building design problems, designers frequently encounter situations where multiple objectives conflict with each other, such as balancing the desire for maximum thermal comfort with the goal of minimizing energy consumption, or optimizing equipment capacity while minimizing costs. Two commonly used methods exist to tackle these challenges. The first method is the weighted sum model, which involves assigning different weights to each objective and combining them into a single cost function. This approach transforms the problem into a single-objective optimization, but its effectiveness heavily relies on the weights assigned to each objective, requiring expertise and experience to determine. The second one is Pareto optimization, which aims to identify the trade-off front, known as the Pareto front, between the competing objectives. The Pareto front is determined based on the concept of dominance, where solutions that are not outperformed in both objectives are considered non-dominated and form the Pareto front. Conversely, solutions that can be improved in both objectives are classified as dominated solutions. Figure 2.23 illustrates a two-objective minimization problem, where the red squares represent non-dominated solutions forming the Pareto front, while the green dots represent dominated solutions. Genetic algorithms have demonstrated notable strengths in solving multi-objective problems, offering valuable insights and solutions (Yang, F., 2017; Nathan C. Brown, 2019).

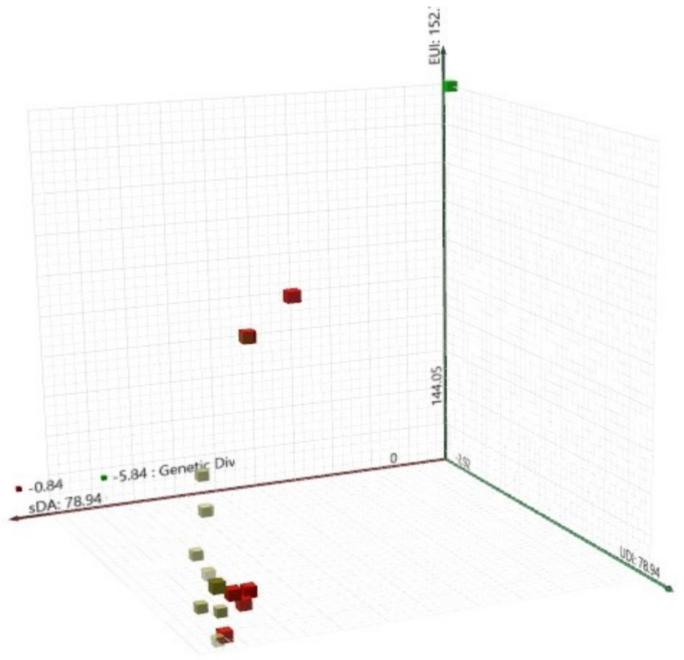


Figure 2.23: Pareto front non- dominated solutions (red dots) and dominated solutions (green dots) (Source: Author, 2022)

In order to effectively utilize these techniques, researchers need to delve into fundamental questions regarding the role of computers in early design stages and how computation can enhance the design process without overpowering it. Throughout this exploration, it remains crucial to uphold the multi-objective perspective provided by optimization techniques and consider essential aspects of their framework. This dissertation retains concepts such as objective prioritization, balancing trade-offs between objectives, satisficing, non-dominated solutions, and other principles from multi-objective optimization. As result, it aims to explore alternative ways of pursuing multi-objective approaches to design that do not adhere strictly to the rigid requirements of traditional optimization methods (Yang, F., 2017; Nathan C. Brown, 2019).

2.3.3 Genetic Algorithms

The Genetic Algorithm (GA) is an evolutionary algorithm inspired by nature's mechanisms. It operates by considering a collection of interconnected genes forming a chromosome, resembling a family. A population of such chromosomes competes against each other to determine the best fitness for a specific objective. Each chromosome undergoes evaluation after each evolution. Following the initial evolution, the breeding process commences, involving the mutation of genes among the fittest chromosomes from the previous evolution. The algorithm continues this breeding process based on the gene configurations within each chromosome until a satisfactory and fittest solution is achieved. In the case of single-objective optimization, the fittest solution corresponds to a vector or point based on the cost function. Figure 2.23 illustrates the mutation settings demonstrated by the Octopus component (section 3.3.2) of the GAs, as part of multi-objective optimization that aim to find solutions to optimize multiple conflicting objectives simultaneously. Depending on the software utilized, designers can adjust these settings in real-time according to their preferences (Reissmüller, J.J, 2015).

For instance, in the field of architecture, an optimization problem may arise in balancing the desire to maximize natural sunlight penetration while minimizing visual discomfort like glare, thereby reducing reliance on artificial lighting. Achieving both goals simultaneously can be challenging as they often conflict with each other. To address this, Genetic Algorithms (GAs) can be employed to optimize the architectural design, ensuring that both criteria are met. This type of optimization, where multiple objectives are considered, is referred to as multi-objective optimization. However, GAs can also be utilized for single-objective optimization, focusing on optimizing either of the two criteria individually. The fundamental framework of a GA as depicted in the Figure 2.24 (Priyadarshini, S. & J. Rashmi.S., 2014; Niclas, 2019).

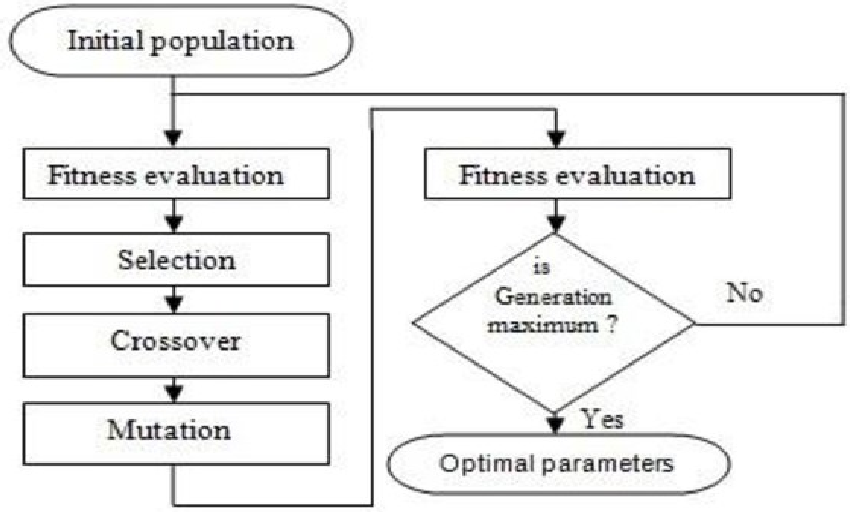


Figure 2.24: The overview of Genetic Algorithms
(Source: Priyadarshini, S. & J. Rashmi.S., 2014)

Selecting the appropriate optimization algorithm is crucial when dealing with different optimization problems. Over the years, numerous types of optimization algorithms have emerged. In their study, Nguyen, Reiter, and Rigo (2014) extensively analyzed various optimization algorithms, categorizing them based on characteristics such as local or global methods, deterministic or stochastic methods, heuristic or meta-heuristic methods, derivative-based or derivative-free methods, bio-inspired or non-bioinspired methods, trajectory or population-based methods, and single-objective or multi-objective algorithms. The strengths, weaknesses, and representative algorithms of each category were thoroughly examined. Similar comprehensive assessments were also conducted by Evins (2013) and Machairas, Tsangrassoulis, and Axarli (2014). Building performance studies often rely on the Genetic Algorithm (GA) as the preferred optimization algorithm. The GA was initially introduced by Holland (1975) in the 1970s as a method inspired by the natural selection process in biological evolution (Galletly, 1998). It operates by iteratively modifying a population of solutions using principles observed in nature, such as selection, crossover, and mutation. The GA selects solutions with favorable performance from the current population as parents to generate the next generation, gradually evolving the population towards an optimal solution (MathWorks, 2022). In fact, optimization packages have gained popularity due to their ease of use, flexibility, and compatibility with familiar software environments, eliminating the need for advanced programming skills. Within the Grasshopper parametric modeling environment, genetic algorithm-based optimization packages are available. One such example is Galapagos, which facilitates single-objective optimization. Another plugin called Octopus, also integrated with Grasshopper, employs genetic algorithm techniques to generate trade-off solutions for multi-objective optimization problems. A study conducted by Zhang, Zhang, & Wang (2016) demonstrated the application of Grasshopper and Octopus in performing multi-objective optimization for a community center building (Zhang, & Wang, 2016; Yang, F., 2017; Niclas, 2019).

Lastly, the Genetic Algorithm and its associated optimization packages offer a practical and accessible approach for optimizing building designs, enabling researchers and designers to explore both single-objective and multi-objective optimization problems within a familiar modeling environment (Niclas, 2019; Yang, F., 2017).

2.4 Conclusion

Parametric design has become an integral part of modern architectural practices, offering numerous benefits and influencing the field in significant ways. Firstly, it provides architects with a powerful framework and computational tools to generate and manage complex and dynamic building forms that were previously challenging to achieve. This capability has revolutionized architectural design, allowing for unprecedented levels of creativity and innovation. Secondly, parametric design fosters collaboration among various experts involved in the design process. Through the integrating specialized tools for performance analysis, architects can work closely with other professionals to optimize design outcomes. This collaborative approach promotes a multidisciplinary perspective, leading to more holistic and efficient design solutions. Thirdly, parametric design introduces a rational and systematic approach to architectural design through the use of rule algorithms. Towards the definition and controlling these algorithms, designers can make informed decisions that result in superior outcomes. This rationality empowers architects to explore a wide range of possibilities and make design choices based on data-driven insights. Parametric design tools offer architects the opportunity to work at multiple levels, combining design knowledge and rule algorithms. This opens up new avenues for exploration and experimentation, expanding the creative possibilities in architecture. However, it is important to acknowledge that with these opportunities, new challenges also arise, which must be addressed to fully leverage the potential of parametric design.

This chapter provides a comprehensive of theoretical development that examines the origins, principles, implementations, and applications of both parametric design concepts and genetic algorithms. The focus of this review is on exploring the relationship between the application of parametric design and its impact on daylighting performance. By delving into the existing body of knowledge, this chapter aims to shed light on the interplay between parametric design and the optimization of daylighting performance.

CHAPTER 3

STATE OF THE ART: PARAMETRIC BASED MULTI-OBJECTIVE OPTIMIZATION FOR DAYLIGHT AND ENERGY PERFORMANCE

REVIEW OF RECENT STUDIES

3.1 Introduction

In recent years, there has been a growing focus on achieving sustainable and energy-efficient buildings that provide optimal daylighting conditions for occupants. Designing buildings that balance both daylighting and energy performance is a complex task, as these objectives often involve conflicting design choices. To address this challenge, researchers have turned to parametric-based multi-objective optimization techniques, which offer a systematic approach to finding optimal design solutions that simultaneously enhance daylighting and energy performance.

The building envelope serves as a physical barrier separating the indoor and outdoor environments, and it plays a significant role in determining the building's performance. Previous research on building envelope optimization has primarily focused on selecting construction types and materials, as well as considering fundamental design variables such as window-to-wall ratio and orientation. The main objectives of optimization in these studies were typically energy performance, thermal comfort, and environmental impact. However, more advanced investigations into complex building shape variables will be discussed in the following section (Yang, F., 2017).

Using bibliometric analysis, this chapter aims to define daylighting and its parametric optimization in order to understand their contribution as passive solutions for reducing energy consumption. It provides a synthesis of literature on the impact of urban morphology on solar potential, allowing the identification of indicator sets and urban morphology parameters that influence the solar performance of buildings through an analysis of existing research.

Moreover, this chapter will present influential researchers working on this topic, the research institutions they belong to, the countries they are affiliated with, the journals publishing the most on the subject, and the most cited research articles. This comprehensive analysis will shed light on the key players and sources of knowledge in the field of daylighting and its parametric optimization.

This paper aims to provide a comprehensive review of recent studies that have explored the application of parametric-based multi-objective optimization for daylighting and energy performance in buildings. By examining these studies, we can gain insights into the state of the art, identify trends, and highlight the effectiveness of these optimization techniques in achieving sustainable and energy-efficient building designs.

One notable aspect of the reviewed studies is the utilization of genetic algorithms, which have emerged as a popular optimization approach in this field. Genetic algorithms mimic the process of natural selection and evolution to iteratively generate and evaluate design solutions based on predefined objectives and constraints. This approach enables the exploration of a wide range of design variables and their combinations, allowing for the identification of optimal solutions that satisfy multiple performance criteria. The studies considered in this review have investigated various aspects of building design, including window size and placement, shading systems, glazing properties, and building orientation, among others. By manipulating these design variables, researchers have aimed to optimize daylighting performance, energy consumption, thermal comfort, and other related factors.

Furthermore, the reviewed studies have employed advanced simulation tools and software platforms, such as Grasshopper, Ladybug, Honeybee, Radiance, Daysim, and EnergyPlus. These tools enable accurate modeling, analysis, and simulation of daylighting and energy performance in buildings, providing researchers with valuable insights into the impact of design choices on building performance. Through their findings, these studies have demonstrated the effectiveness of parametric-based multi-objective optimization in achieving sustainable building designs. By considering multiple objectives and constraints, such as daylight availability, energy consumption, thermal comfort, and occupant well-being, researchers have been able to identify optimal design solutions that strike a balance between these factors.

In conclusion, the reviewed studies highlight the state of the art in parametric-based multi-objective optimization for daylighting and energy performance in buildings. These studies demonstrate the potential of these optimization techniques in achieving sustainable and energy-efficient building designs. By leveraging advanced simulation tools and considering a wide range of design variables, researchers can create optimized building designs that enhance daylighting conditions, minimize energy consumption, and improve the overall indoor environment for occupants. The insights gained from these studies provide valuable guidance for future research and development in this field.

3.2 Studies using genetic algorithms approach in building optimization of daylight and Energy performance

The optimization of daylight performance in buildings has gained significant attention in recent years, with researchers exploring various approaches to achieve optimal daylighting conditions. One approach that has emerged as a promising method is the use of genetic algorithms. This bibliographic analysis aims to provide an overview of recent studies that have utilized genetic algorithms in the context of building optimization for daylight performance.

By examining these studies, we can gain insights into the methodologies, findings, and trends in this field.

Several studies have focused on optimizing the daylight and Energy demand of buildings. As in a study conducted by Ahmed Toutou (2019) which titled "The parametric based optimization framework daylighting and energy performance in residential buildings in hot arid zone" (see Figure 3.1), this research paper delves into the potential of employing a parametric design optimization approach within residential buildings to enhance sustainability in design. The investigation revolves around the refinement of building parameters, including factors like WWR, construction and glass materials, as well as configurations of shading devices. The primary objective is to attain optimal performance concerning both daylighting and energy consumption. The optimization procedure is executed through a self-contained loop framework comprising parametric modeling, building performance simulation, and a genetic algorithm. Diverse computational tools, including Grasshopper, Octopus, EnergyPlus, Open studio, Radiance, and Daysim, are harnessed to accomplish a finely tuned parametric design. The research's purpose lies in elevating the computer's role within the design process beyond being merely a drafting or visualization tool, aiming to activate its potential as a significant contributor.

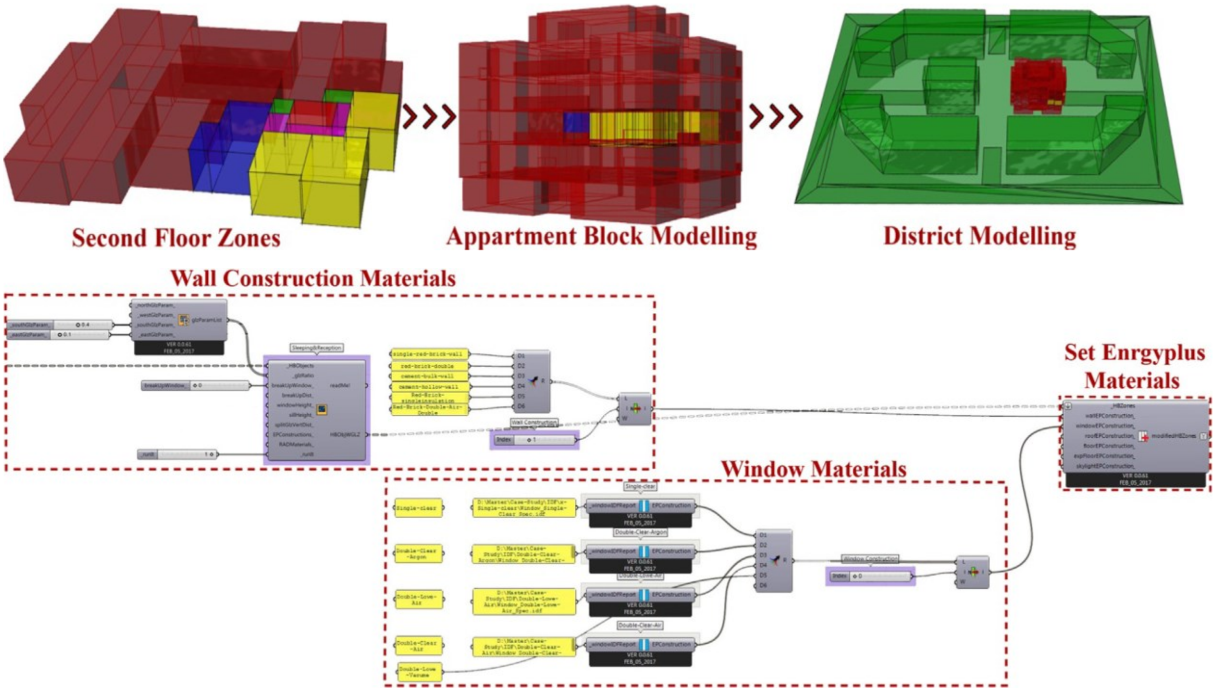


Figure 3.1: Daylighting energy simulation (Source: Ahmed Toutou et al., 2019)

In another study, that performed by Yaser Shahbazi (2019), which centers on the enhancement of office building facades with the aim of achieving superior energy efficiency and optimal daylight provision. The authors underscore the crucial need to strike a harmonious equilibrium between ensuring ideal daylight comfort and utilization while concurrently maximizing thermal effectiveness. They advocate for the application of a parametric design model to simulate lighting and annual thermal performance during the initial phases of design or renovation endeavors. The investigation introduces six meticulously fine-tuned designs for the building's corner zones, alongside four optimized designs for the side zones. The findings affirm the substantial influence of window arrangements on a building's energy efficacy. In summation, the paper underscores the critical significance of a comprehensive assessment encompassing energy requirements for heating, cooling, lighting, and daylighting simulations, all of which contribute to the meticulous optimization of a building façade (see Figure 3.2).

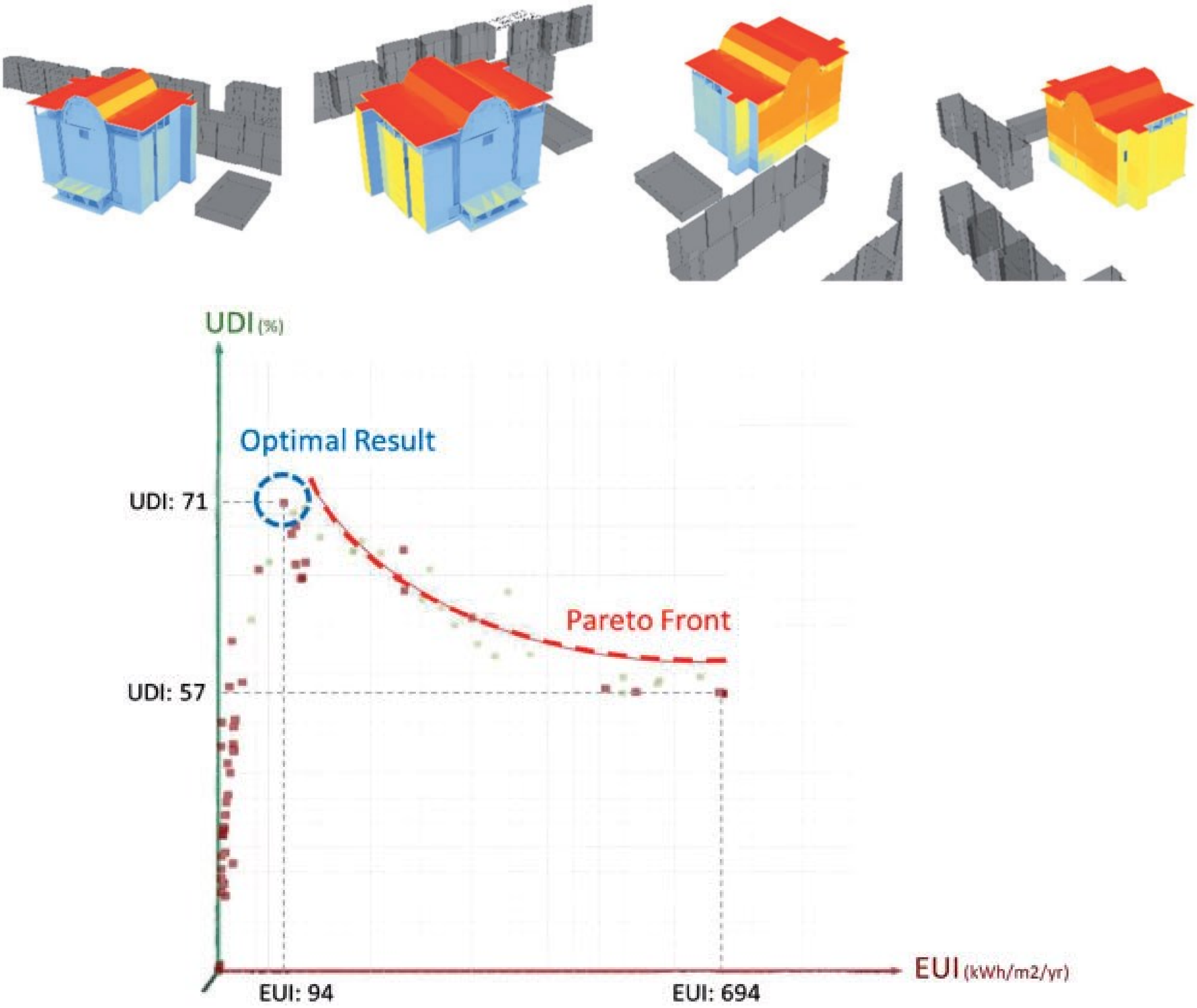


Figure 3.2: Octopus chart. EUI: energy use intensity; UDI: useful daylight illuminance. (Source: Yaser Shahbazi, 2019)

The outcomes of the study reveal that the configuration of windows exerts a notable influence on the energy efficiency of a building. The research introduces six meticulously refined designs tailored for the building's corner zones, along with an additional four optimized designs for the side areas. By employing the devised workflow, the improvements yielded an impressive 20.56% enhancement in useful daylight illuminance and a substantial 141 kWh/m2/yr reduction in energy use intensity. The utilization of the Honeybee plug-in, coupled with the reintegration of energy and daylighting simulation outcomes, empowers designers to visually map geometry results. Through Honeybee, users can explore outcomes through a variety of distinctive visualization components. For instance, in UDI simulations, the percentage of UDI can be effectively visualized through a color-coded grid. Additionally, the results pertaining to thermal energy demand were graphically presented in a chart, effectively displaying energy consumption for lighting, heating, and cooling on a month-to-month basis throughout the year.

In a research paper by NADIRI P. and colleagues (2019), the primary focus lies in the optimization of building facades to regulate daylight ingress and enhance visual comfort. The study delves into the impact of diverse parameters of shading louvers oriented towards the south in Tehran, Iran (Refer to Figure 3.3). For simulations, Rhino/Grasshopper plug-in was employed, and the Galapagos evolutionary solver component facilitated the optimization process. The investigation yields the insight that it is indeed feasible to achieve an interior space visibility of approximately 90% while simultaneously maintaining the Annual Sun Exposure (ASE) value within a reasonable threshold. The article acknowledges the constraints inherent in the study and underscores the necessity of evaluating the outcomes within an actual room setting. The research establishes the potential to attain extensive interior space views without compromising the ASE value, and simultaneously, it underscores the need for real-room assessments due to the study's inherent limitations.

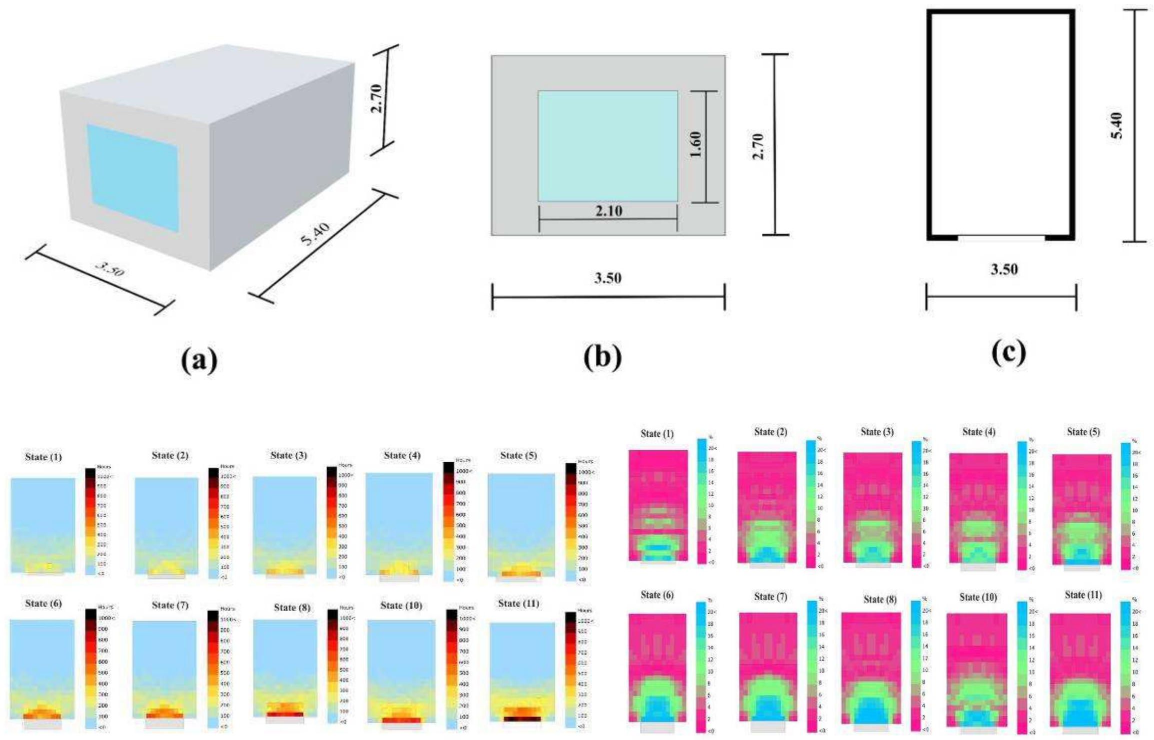


Figure 3.3: The view percentage in the input geometry for 10 optimal solutions
(Source: NADIRI P. et al., 2019)

Sun, C. et al., (2020), introduces an architect-centered approach for optimizing design using artificial neural networks (ANN) to enhance energy efficiency, daylighting, and cost-effectiveness in a large-scale public building. This method was applied to a public library in Changchun, China, with a focus on optimizing Energy Use Intensity (EUI), Spatial Daylight Autonomy (sDA), Useful Daylight Illuminance (UDI), and Building Envelope Cost (BEC). This optimization process yielded a set of 176 non-dominant solutions. By employing the chosen optimal solutions, an annual energy saving of 1.6×10^5 - 2.1×10^5 kWh was achieved. Additionally, sDA and UDI values saw an increase of 8.1% - 11.0% and 4.3% - 4.7%, respectively. Moreover, BEC witnessed a reduction of ¥1.2×10^5 - 2.1×10^5 ($1.7×10^4 - 3.0×10^4). A remarkable aspect of the proposed method is its high efficiency, as it eliminates the need for manual data conversion between various platforms.

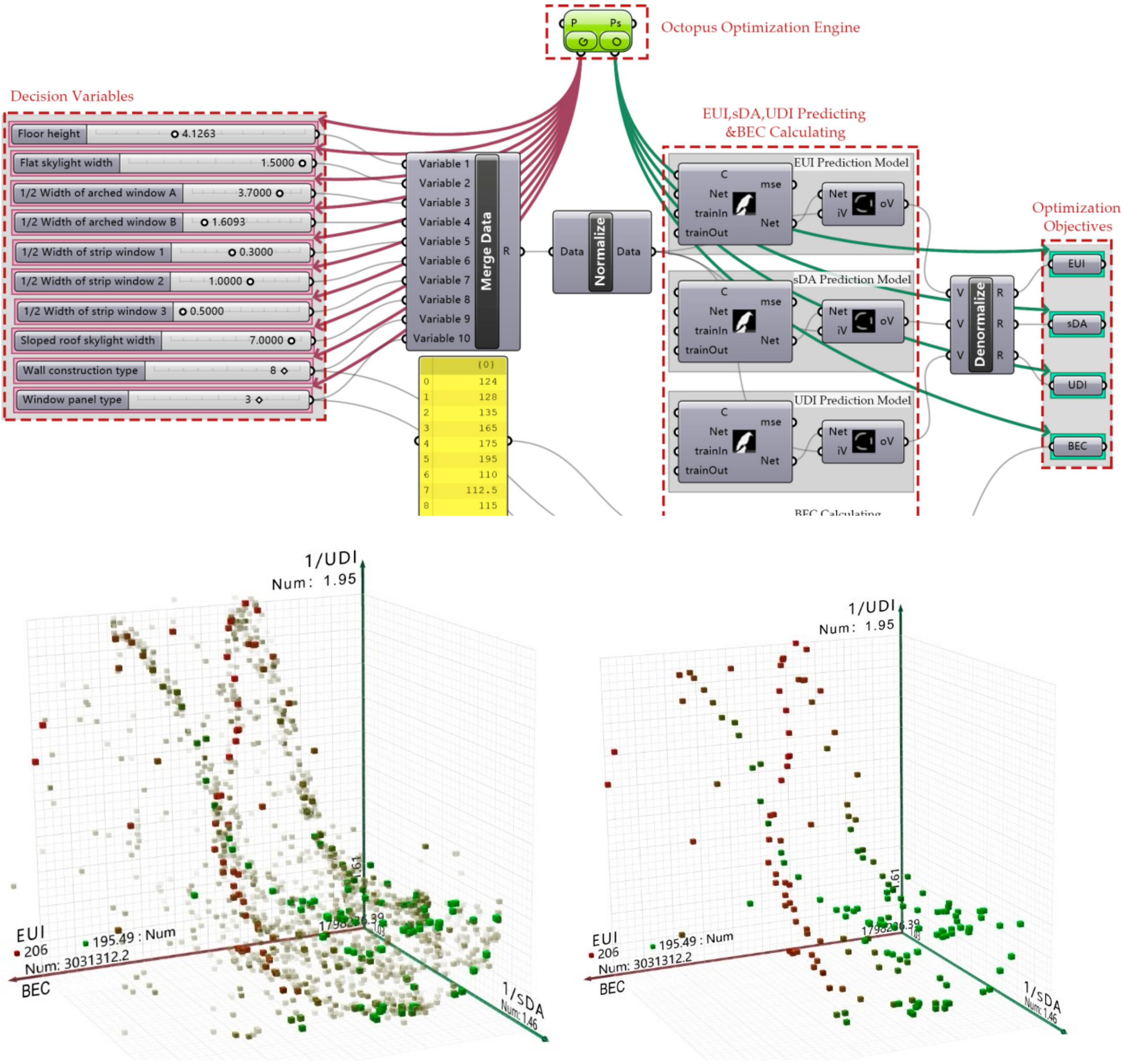
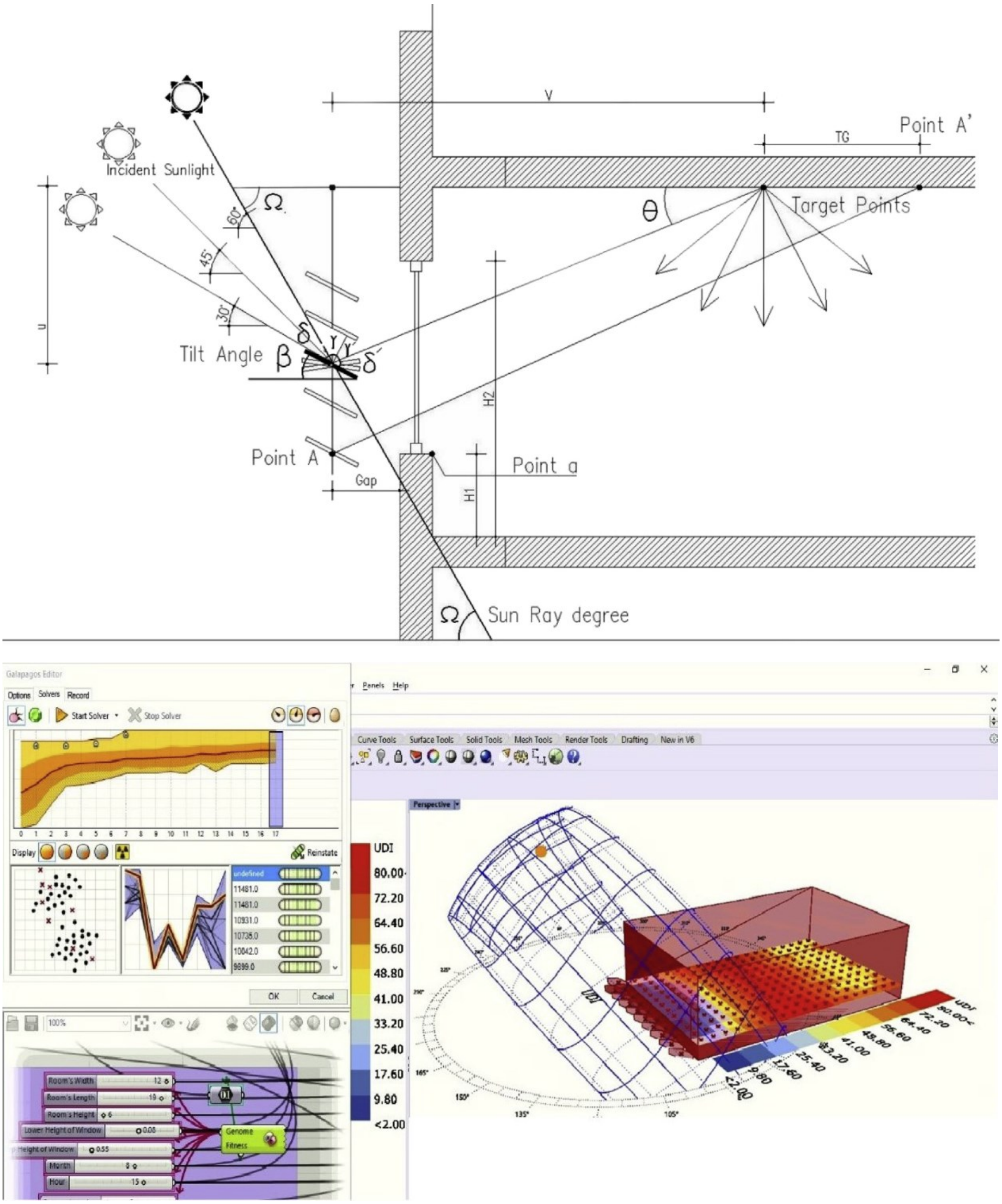


Figure 3.4: Many-objective optimization module and results (Source: Sun, C. et al., 2020)

Another study of Samadi, S. et al. (2020), which conducted for enhancing the indoor daylight conditions within a building by devising a kinetic shading system comprised of distinct units that independently respond to sunlight via 3D rotation and 2D movement, enabled through parametric design. These units were meticulously defined utilizing the "Grasshopper" plugin, with their rotation parameters dynamically controlled based on sun path and weather data, facilitated by the "Honeybee" and "Ladybug" plugins. This approach ensured a consistently optimized daylighting experience within the building. The shading units' ideal configuration was identified as a hexagon, and the "Galapagos" plugin was utilized to assess this pattern, aiming to maximize the desired UDI (ranging from 100 to 2000).

The outcomes revealed that the implementation of such a shading system, under optimal conditions, can significantly amplify the efficacy of indoor daylighting (see Figure 3.5).



undefined
11481.0
11481.0
10931.0
10735.0
10042.0
9899.0

Room's Width 12
Room's Length 19
Room's Height 6
Lower Height of Window 0.05
Height of Window 0.55
Month 8
Hour 15

Figure 3.5: Optimization of the model based on UDI with using “Galapagos” optimization component (Source: Samadi, S. et al., 2020)

Kheiri, F. (2021) performed a study showcases the outcomes obtained from diverse optimization approaches employed in the design of high-performance glazing and shading systems (refer to the figure 3.6). The enhancements achieved through each optimization procedure are visually depicted, including the variations in Spatial Daylight Autonomy (sDA) and Annual Sun Exposure (ASE) across all instances. An assessment of the dependability, uniformity, and resilience of these optimization methods, gauged through mean and variance analyses of the objective function values from the most favorable cases in distinct methods, brings to light a notable distinction between the hybrid GA/SA with elevated temperature and the conventional GA. Notably, the hybrid algorithm demonstrated superior performance compared to the GA in this context.

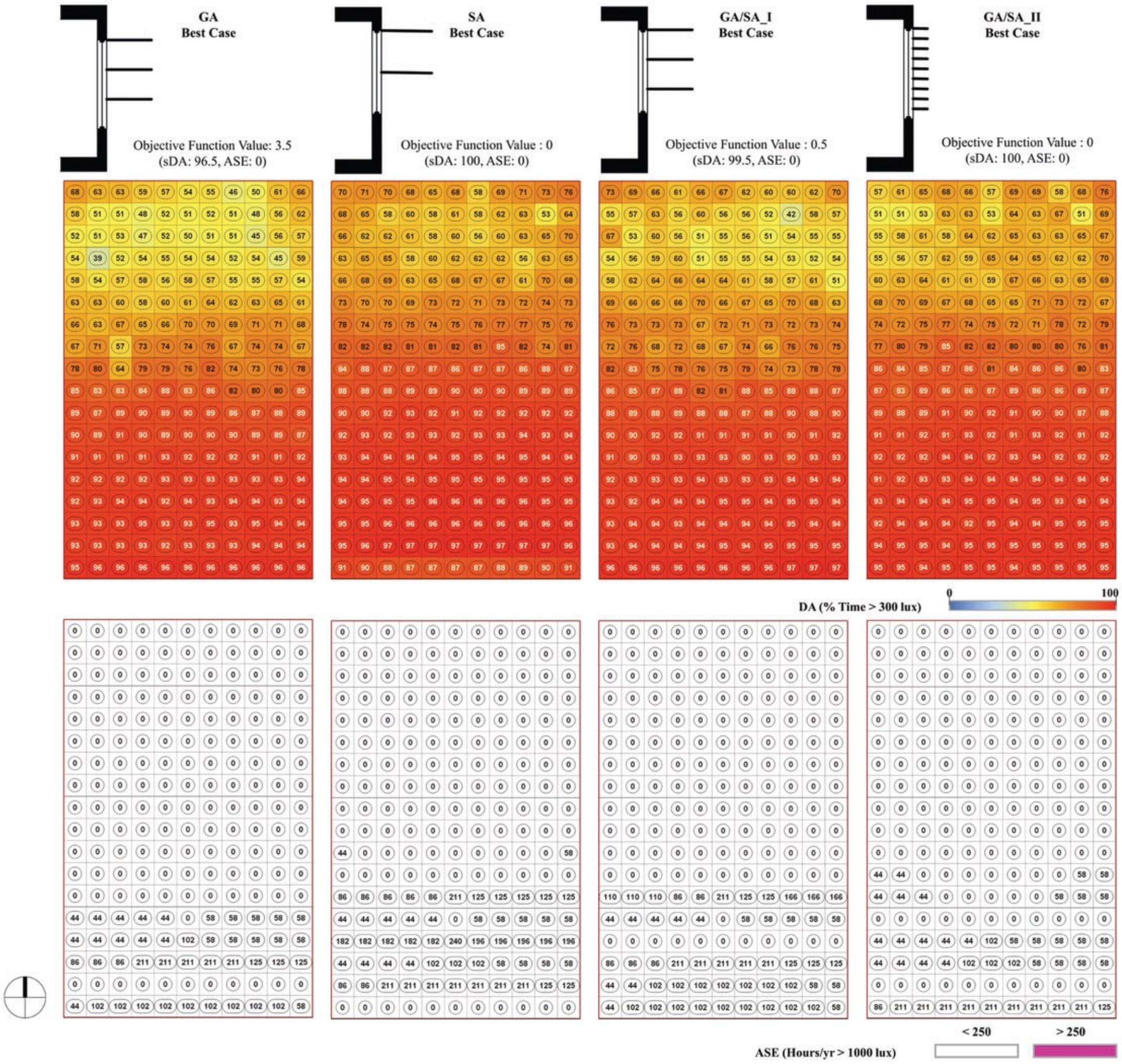


Figure 3.6: Detailed illustration of the best alternatives found using each algorithm. ASE: annual sunlight exposure; GA: genetic algorithm; sDA: spatial daylight autonomy; SA: simulated annealing (Source: Kheiri, F., 2021)

Another study of Ali Ahmed Salem Bahdad et al. (2020), that introduces an optimization procedure tailored to support architects in evaluating the daylighting efficiency of diverse design alternatives for a fully glazed facade featuring an integrated light shelf system, all within Malaysia's tropical climate. This method employs parametric design, simulation modeling, and genetic algorithms. The findings from the optimization phase reveal that the carefully selected light-shelf parameters within the optimal design alternatives exhibit significant potential for enhancing illuminance levels. Following the optimization process, the useful daylight illuminance performance experiences notable enhancement compared to reference models, indicating an average increase of 15.6% and 4.7% on June 21st, 17.5% and 5.8% on March 21st, and 5.8% and 11.3% on December 21st. The research also undertakes a statistical analysis to scrutinize the relationship between performance metrics of the optimal designs and alternative cases. The outcomes demonstrate that regression analysis yielded a high degree of reliability, along with varying levels of variation coefficients (see Figure 3.7). The research paper additionally proposes potential future endeavors, which could encompass extending this optimization approach to various daylight-related facets, such as thermal comfort, visual comfort (glare likelihood), and energy conservation.

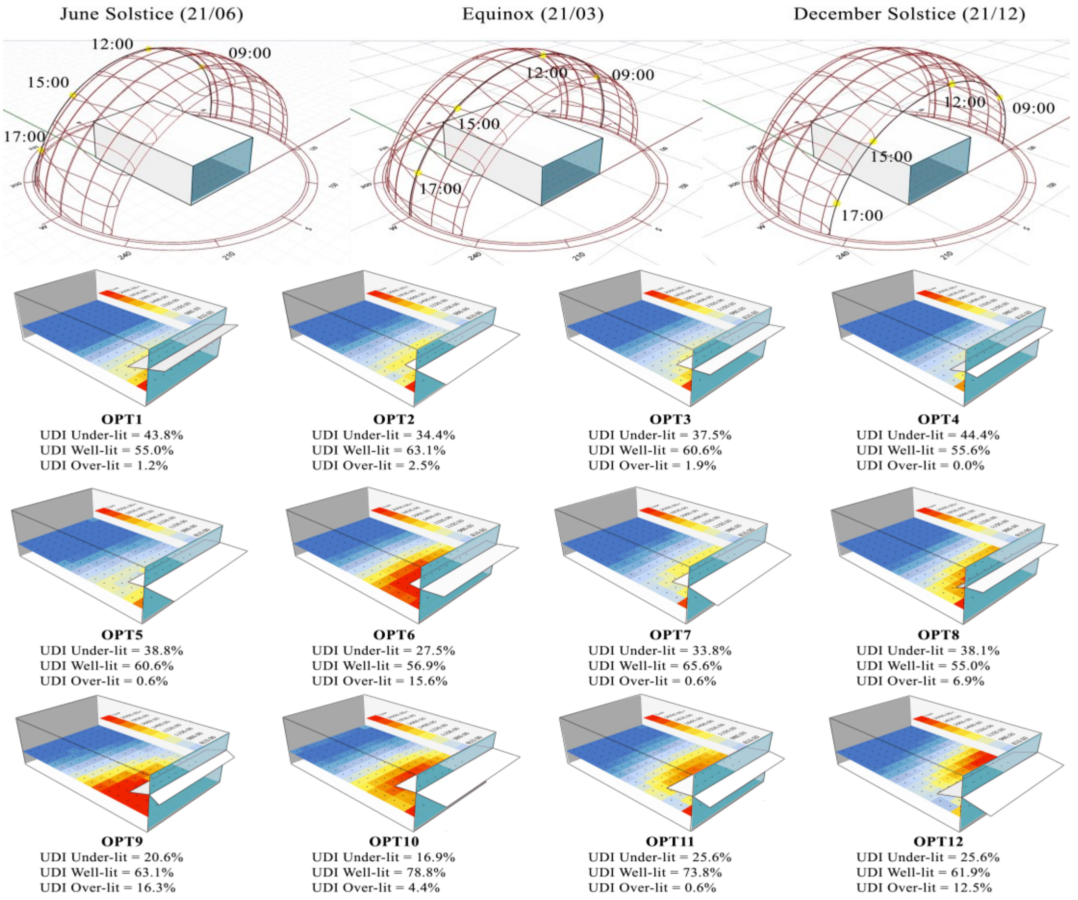


Figure 3.7: The optimal light shelf parameters design options

(Source: Ali Ahmed Salem Bahdad et al., 2020)

Amir Tabadkani et al. (2018), discusses the creation of a parametric analytical methodology aimed at assessing both daylighting and visual comfort by integrating a shading system responsive to sunlight. The primary aim is to forecast yearly metrics associated with daylight and potential occurrences of indoor glare discomfort. The investigation explores the quality of indoor daylight across various geometric and physical attributes, leveraging two distinct geometric elements (Rosette modules and louvers) and generating an expansive array of 6480 design variations. The proposed approach exhibits a significant capacity to enhance shading adaptability, thereby exerting control over both daylight metrics and glare. This is achieved through a fully adaptive pattern with the potential to achieve optimal visual comfort levels, aligning with the criteria stipulated in the LEEDv4 certification. The study outcomes are presented through a specialized tool named the Design Explorer, intentionally developed to visually present the substantial volume of daylighting outcomes derived from the parametric analysis (see Figure 3.8).

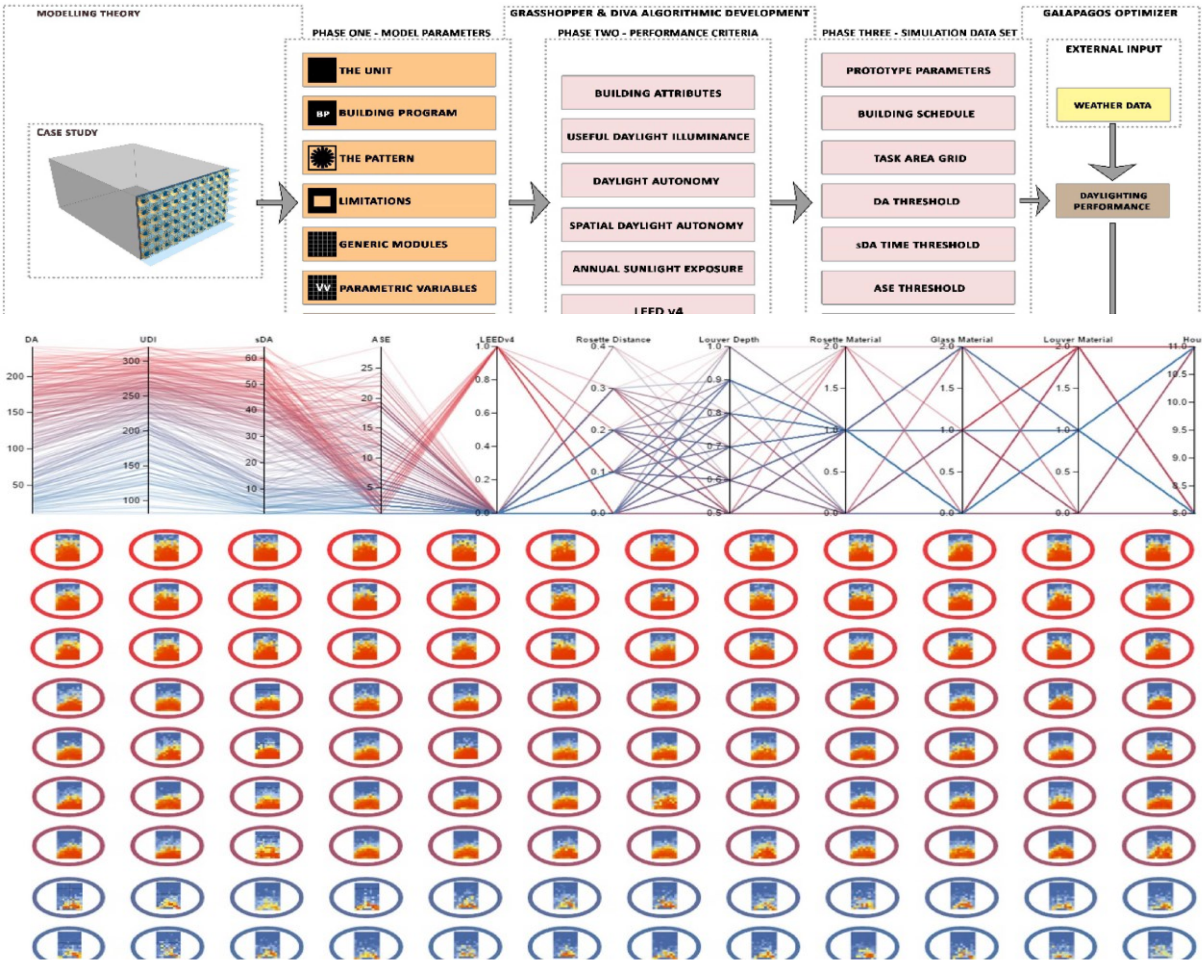


Figure 3.8: The performance of unprotected skin vs. louver and Rosette protection

(Source: Amir Tabadkani et al., 2018)

Also A. Sherif et al., (2015), determine the optimal window sizes and shading configurations to ensure sufficient daylight, prevent glare, and minimize energy usage for ICU windows in desert settings, specifically focusing on Cairo, Egypt. The research concluded that employing shading systems played a pivotal role in achieving satisfactory daylight performance and energy conservation. Meticulously orienting the ICU window significantly contributed to improved functionality. Notably, ICU windows oriented northward offered the broadest array of successful window configuration options across different Window-to-Wall Ratios (WWRs). Those facing south also presented a reasonable number of viable options. In contrast, ICU windows facing east displayed limited choices that could ensure acceptable performance. The application of horizontal sun breakers and solar screens to shield ICU windows outperformed alternative solutions across a wide range of WWRs, proving more effective. Furthermore, the study quantified the annual energy savings achievable by adopting the examined window sizes and shading systems in comparison to a base-case scenario. The outcomes demonstrated the exceptional efficacy of external solar screens in curtailing energy consumption, resulting in noteworthy energy savings across various WWRs. Notably, these screens yielded the highest energy-saving values, reaching an impressive 45%.

Ayman Wagdy et al. (2017), conducted a study that shows the fundamental attributes of external sun-breakers suitable for managing solar exposure within hospital patient rooms when clear skies prevail. The study specifically addressed the distinct configurations of patient room designs, encompassing both the inboard bathroom and outboard bathroom layouts. The findings of this investigation discerned the optimal range of cut-off angles for the sun-breakers, alongside their corresponding tilt angles, ensuring optimal daylighting performance for the varying patient room types across different Window-to-Wall Ratios (WWRs). The study encompassed a comprehensive total of 308 scenarios, with a notable observation that effective daylighting outcomes were attained when cut-off angles fell within the span of 50° to 54° for all tested WWRs, catering to both inboard and outboard bathroom layouts. Notably, horizontal sun-breakers consistently delivered successful outcomes across the spectrum of WWRs for both patient room configurations. Furthermore, with increasing WWRs, the acceptance rate of such configurations rose for both patient room designs. The paper offers meticulous tables and visuals that lucidly depict the permissible spectrum of sun-breaker setups for each of the scrutinized WWR conditions (see Figure 3.9).

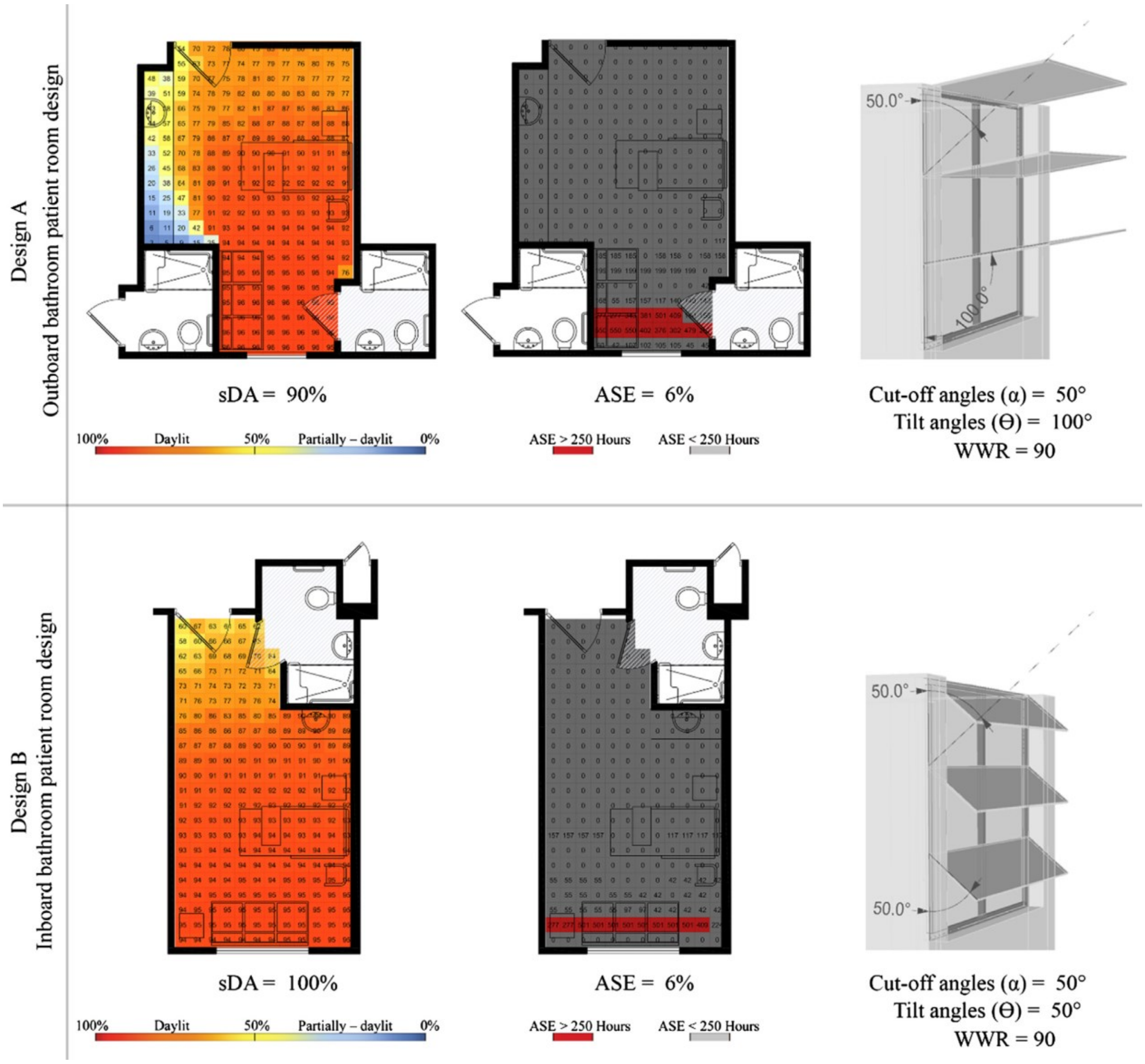


Figure 3.9: Sample of the simulation results of one of the frequently accepted sun-breaker configuration (Source: Ayman Wagdy et al., 2017)

In conclusion, the bibliographic analysis of these studies underscores the effectiveness of employing genetic algorithms in building optimization to enhance daylight performance. These studies demonstrate the capability of genetic algorithms to identify optimal solutions by considering multiple design variables and objectives. By harnessing the power of genetic algorithms, researchers and practitioners can improve daylighting conditions in buildings while simultaneously achieving energy efficiency goals. The insights and methodologies provided by these studies serve as valuable resources for further research and advancements in this field.

3.3 Studies using genetic algorithms approach in building optimization of daylighting, energy demand and thermal comfort

Attaining sustainability objectives within the construction domain necessitates structures that excel in energy efficiency while simultaneously enhancing the indoor environment for occupants. Consequently, numerous researchers have delved into the building envelope, aiming to identify optimal shading solutions that cater to daylighting and thermal comfort. These shading devices assume a pivotal role in realizing the principles of sustainable architecture.

In this context, Zhang et al. (2019) conducted a study introduces a parametric strategy aimed at enhancing the performance of residential building designs in Beijing (see Figure 3.10). This method encompasses the selection of 27 distinct design parameters relating to both residential spatial configuration and building envelope, which are subsequently subjected to optimization. The central focus of this optimization process revolves around cooling and heating load simulations. The resulting optimized schemes emerge from a comprehensive set of 6246 simulation outcomes, of which 1925 were rigorously validated, affirming the reliability of the optimized results. A thorough analysis was conducted to unveil correlations between design parameters and performance metrics, aiming to provide architects with a straightforward means of determining optimal design parameters based on the sensitivity of each parameter's impact on performance. The optimization outcomes reveal a notable reduction in the total load of the optimal scheme by 0.86 W/m2 (equivalent to an 18.1% decrease) when compared to the original scheme. Furthermore, this reduction becomes even more pronounced, amounting to 2.02 W/m2 (equivalent to a 48.1% decrease), in contrast to the least favorable scheme. Importantly, these outcomes align with the fourth stage of building energy-saving standards, denoting a substantial energy consumption decrease as stipulated by relevant standards. Specifically, the research indicates that newly designed residential buildings should achieve a 30% reduction in energy consumption compared to the third-stage standards and a remarkable 75% reduction relative to the 1981 benchmark building energy consumption.

In summation, the study establishes the effectiveness of the parametric optimization approach in aligning with energy standards during the early design phase of residential projects. This approach holds the potential to yield an energy consumption reduction ranging from 10% to 20%, showcasing its significance in promoting energy efficiency within the realm of residential design.

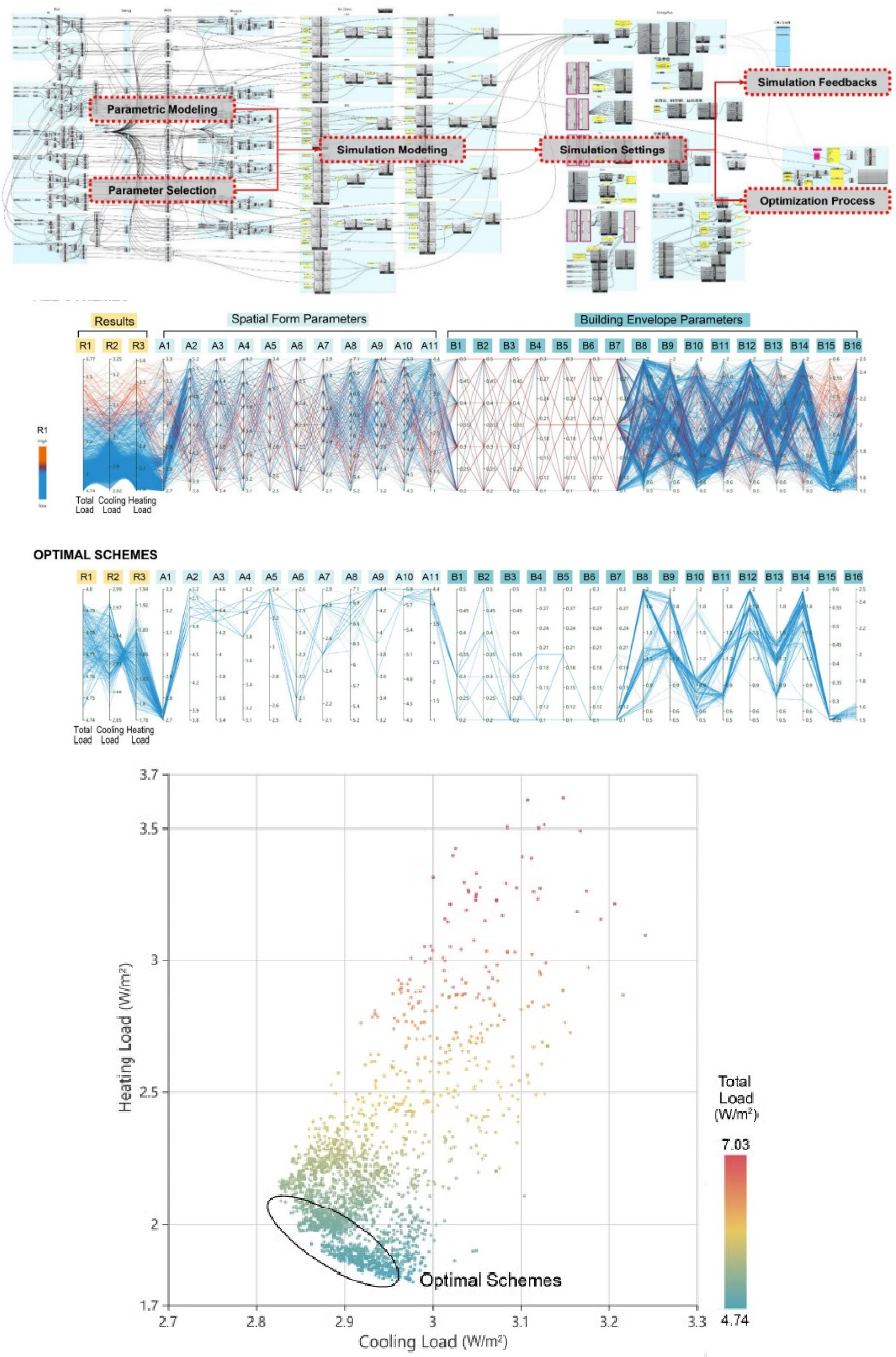
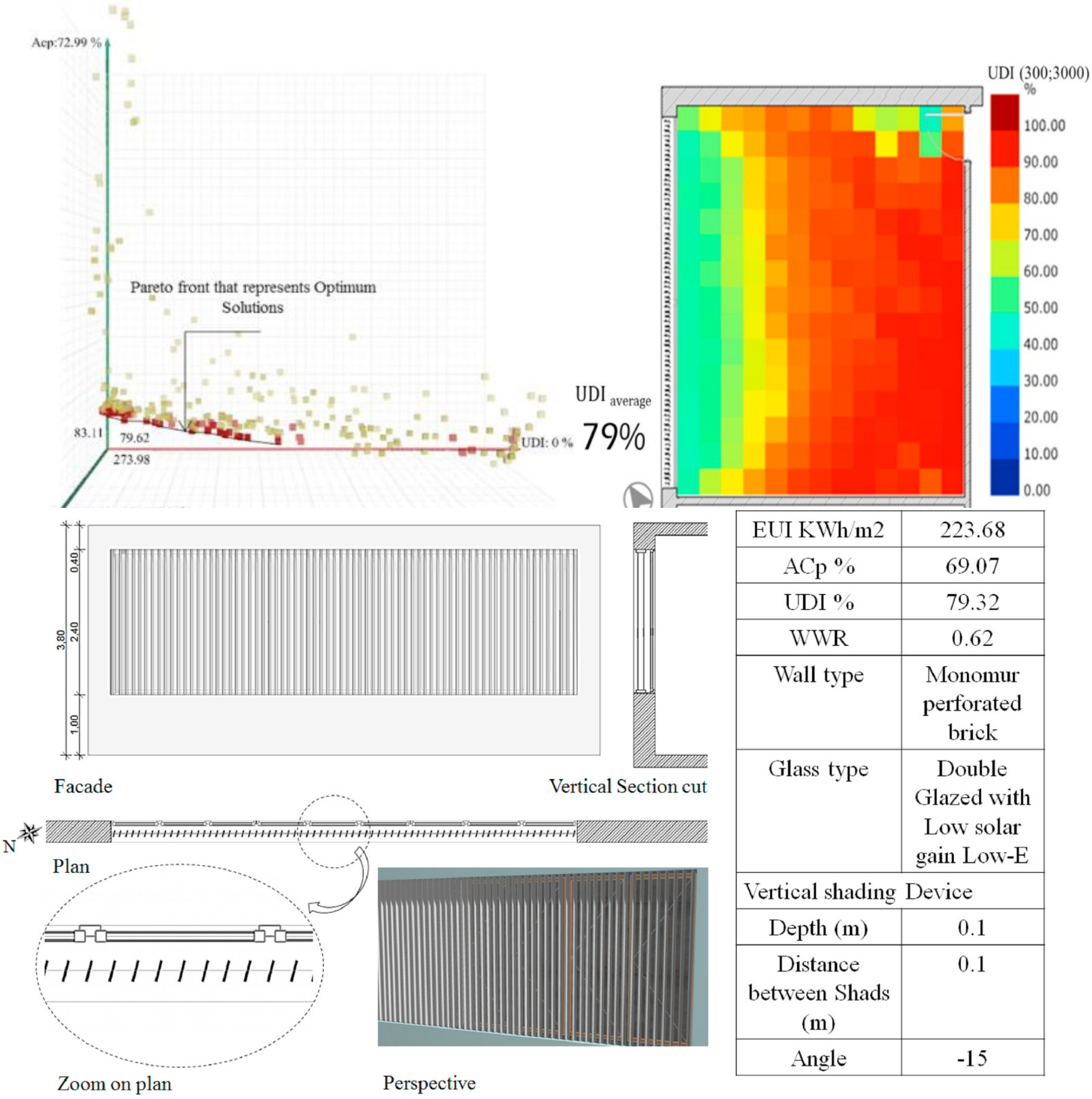


Figure 3.10: Thermal load scatter plot of all schemes (Source: Zhang et al., 2019)

In a comparable investigation conducted by Lakhdari et al. (2021), a parametric optimization strategy was employed to enhance the daylighting, thermal, and energy performance of a college classroom situated in a hot and arid climate. The objective of this endeavor was to achieve well-balanced classroom designs that effectively manage a multitude of interconnected factors, a particularly complex task in hot and arid settings. Leveraging the Octopus plug-in within Grasshopper, a multi-objective evolutionary computation was carried out, encompassing various parameters such as the window-to-wall ratio (WWR), wall materials, types of glass, and shading mechanisms. The underlying aim was to uncover potential design solutions that strike an optimal equilibrium between daylight provision, thermal comfort, and energy efficiency. In the preliminary phase of the study, meticulous measurements were undertaken to evaluate the daylight levels and temperatures within the designated classroom. The findings exposed inadequate daylight during occupancy hours, resulting in a notable dependence on artificial lighting and depriving occupants of the inherent advantages of natural illumination. These empirical findings were then employed to validate the simulation model and quantitatively assess the performance of the baseline case.

Subsequently, an array of optimization parameters were carefully selected and incorporated into a multi-objective optimization process rooted in Pareto optimality theory. The primary objective encompassed the pursuit of an optimal classroom design solution that simultaneously maximizes daylighting and thermal performance while minimizing energy consumption (as illustrated in Figure 3.11). To actualize this objective, pertinent building performance metrics were identified. The Uniform Daylighting Index (UDI) metric, encompassing the range of 300-3,000 lux, was adopted as a measure and optimization target for daylighting performance. The thermal Adaptive Comfort Percentage (ACP), determined using the Grasshopper Ladybug and Honeybee plug-ins, emerged as a means to gauge the classroom's thermal comfort conditions. Furthermore, the Energy Use Intensity (EUI) metric was harnessed to optimize energy consumption. Through the integration of these optimization parameters and the application of a multi-objective methodology, Lakhdari et al. (2021) aimed to ascertain an optimal classroom design that effectively addresses the intricate considerations of daylighting, thermal comfort, and energy efficiency, all within the challenging context of a hot and arid climate.



EUI KWh/m2	223.68
ACp %	69.07
UDI %	79.32
WWR	0.62
Wall type	Monomur perforated brick
Glass type	Double Glazed with Low solar gain Low-E
Vertical shading Device	
Depth (m)	0.1
Distance between Shads (m)	0.1
Angle	-15

Figure 3.11: Pareto front results Optimum solution model and related parameters (Source: Lakhdari et al., 2021)

A study of Sahnoune, S (2022), centers on the conceptualization of courtyards and their influence on indoor thermal comfort and solar regulation. The paper explores the manipulation of distinct geometric factors, such as the height/width ratio and orientation, to optimize wind manipulation and indoor thermal comfort within courtyard layout. The investigation underscores the significance of rectangular, enclosed courtyards in offering shade during scorching days, particularly within hot-arid, semi-arid, and hot-humid climatic conditions. Employing the Ladybug software, the paper conducts simulations on chosen test scenarios, with the outcomes. In its culmination, the study presents a framework for integrating these insights into other architectural designs, aligning with solar control principles (see Figure 3.12).

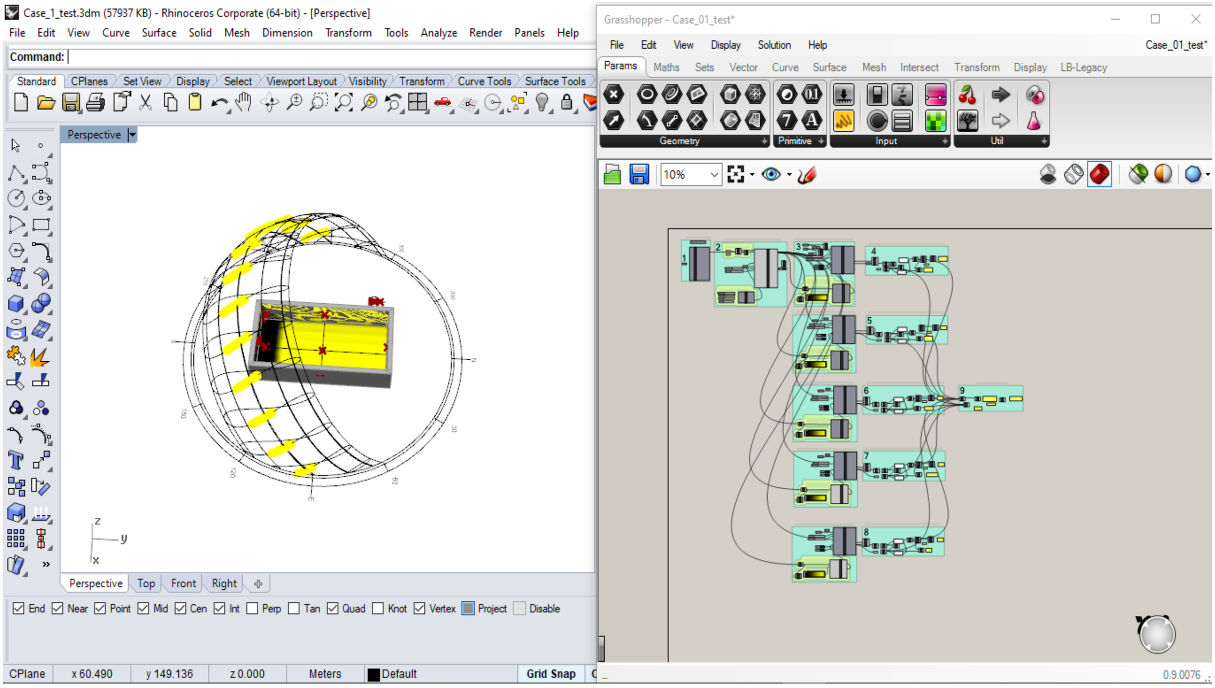


Figure 3.12: Example of a day’s visualisation of the Asunlight in the courtyard in Rhinoceros 5.0 (Source: Sahnoune, S, 2022)

The paper outlines the outcomes of multi-objective optimization investigations conducted over eight generations to establish optimal correlations between Asunlight and Ashading. Utilizing the Ladybug software, the study simulated the performance of carefully selected test cases and expounds on the findings. The results reveal a consistent enhancement across successive generations, with each new generation featuring genomes of superior fitness compared to its predecessor. The optimal solution's objective function values for the eight generations are recorded as 69.79, 70.66, 70.73, 71.10, 71.38, 76.36, 76.42, and 70.32, respectively. Notably, a marginal advancement was observed during Generation 2 and Generation 4 upon scrutinizing these outcomes (see Figure 3.13).

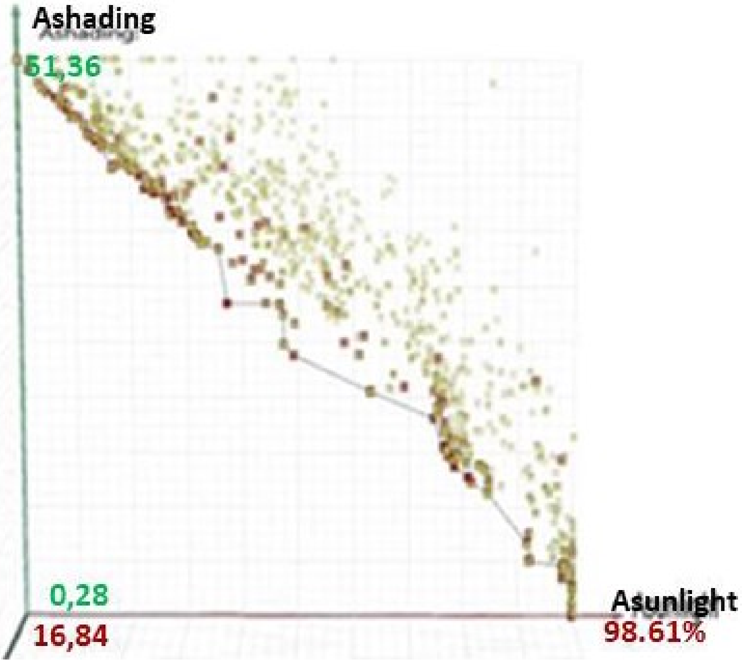


Figure 3.13: Pareto front of last generation (Source: Sahnoune, S, 2022)

This research paper holds significant practical implications encompassing various domains as; the framework proposed herein offers a comprehensive guide to fashioning courtyards that harmonize with sustainability and ecological sensibilities. Through harnessing solar and wind energy for passive temperature regulation, these courtyards deliver year-round thermal solace to inhabitants. The study underscores the criticality of judiciously selecting geometric parameters, optimizing orientation in accordance with climatic nuances, shaping appropriate apertures, incorporating sustainable materials, establishing optimal wall thickness to amplify thermal capacity, and deploying energy-efficient insulation. The integration of vegetation and water bodies further enriches the courtyard's climatic adaptability, either ameliorating or mitigating its thermal attributes. Furthermore, the paper forwards a blueprint for transposing these findings into diverse architectural contexts, fostering a synergy between solar control and design ingenuity. Architects, designers, and building proprietors stand to leverage the outcomes of the multi-objective optimization investigations, empowering them to decipher the most propitious correlations between solar exposures (Asunlight) and shading (Ashading) tailored to their specific geographic locales and latitudes (Refer to the Figure 3.14). The paper also offers pragmatic design recommendations, meticulously calibrating geometric elements to optimize shading and sunlight ingress. This guidance profoundly benefits professionals working across distinct geographical terrains and latitudinal zones (Sahnoune, S, 2022).

Ultimately, the insights amassed through this research bear the potential to elevate the outdoor thermal comfort and energy efficiency of courtyards across diverse climatic enclaves, marking a decisive stride towards holistic and sustainable architectural practice.

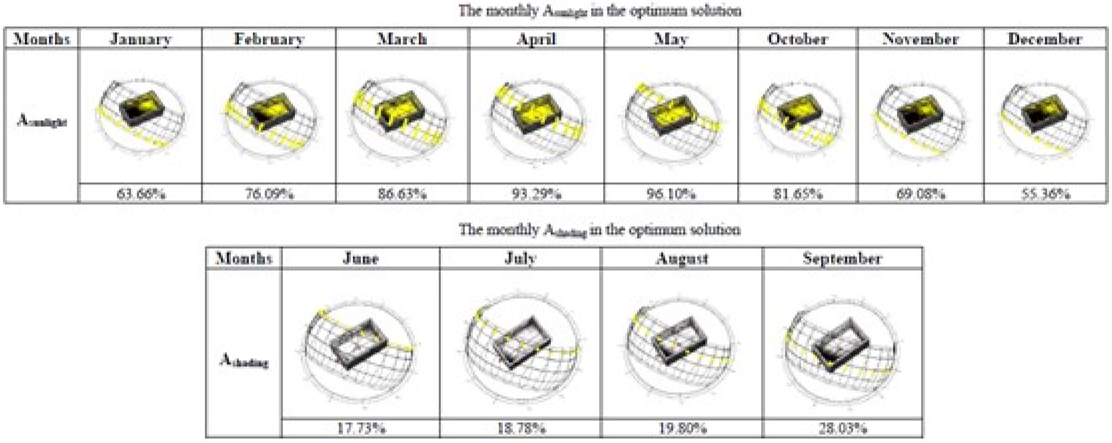


Figure 3.14: The monthly A shading and A sunlight in the optimum solution
(Source: Sahnoune, S, 2022)

Another study of Yan, H. et al. (2022), is dedicated to enhancing the daylight and thermal performance of office building facades in Nanjing, China (see Figure 3.15). The authors introduce an approach encompassing random sampling of design models, streamlined assessment of daylight performance criteria, and the selection of optimal solutions. The study's objective revolves around enhancing indoor lighting uniformity and reducing indoor illumination levels in comparison to an unshaded reference building. Furthermore, the building facade aids in achieving a more balanced distribution of solar radiation received by office buildings during both summer and winter seasons. The research yields six sets of meticulously optimized solutions that fulfill the prescribed criteria. This proposed optimization design methodology for building facades holds considerable potential as a guiding framework for office buildings situated in Nanjing. The paper further explores the development of an innovative parametric design approach tailored to building facades within the context of the Yangtze River Delta region in China. The algorithms for parametric design and shape generation are comprehensively examined, and their applicability to shaping building facades is systematically summarized.

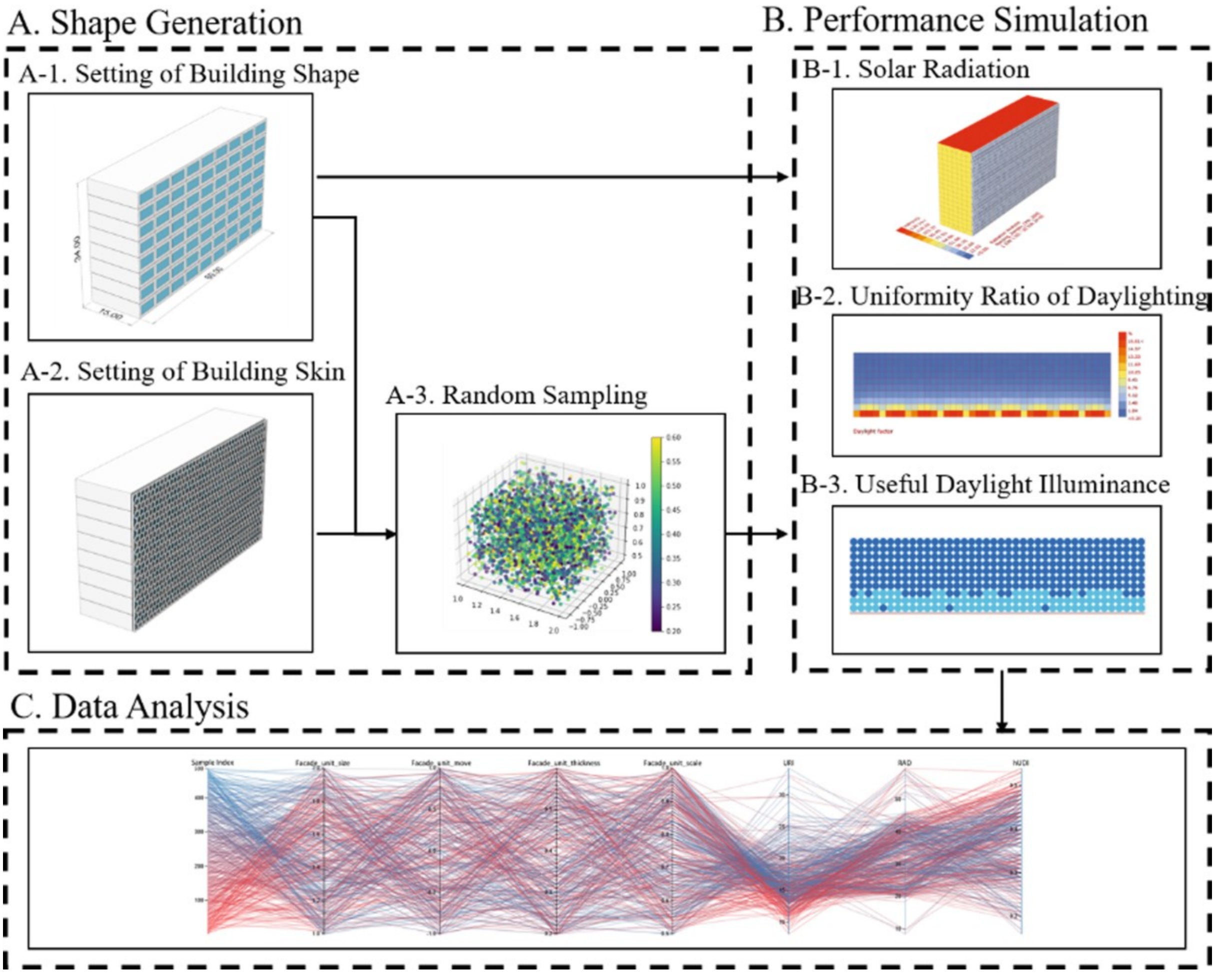


Figure 3.15: Approaches and Techniques Employed in Research (Source: Yan, H. et al., 2022)

The outcomes of the study underscore that building facades play a pivotal role in enhancing indoor lighting uniformity while curbing indoor illumination levels in contrast to unshaded reference buildings. Additionally, the building facade contributes to achieving a more equitable distribution of solar radiation, promoting a balanced climate within office buildings during both summer and winter. The study yields a comprehensive compilation of six meticulously optimized solutions adhering to specified filtering requirements. The proposed optimization design methodology for building facades bears significant guidance potential for office buildings in Nanjing.

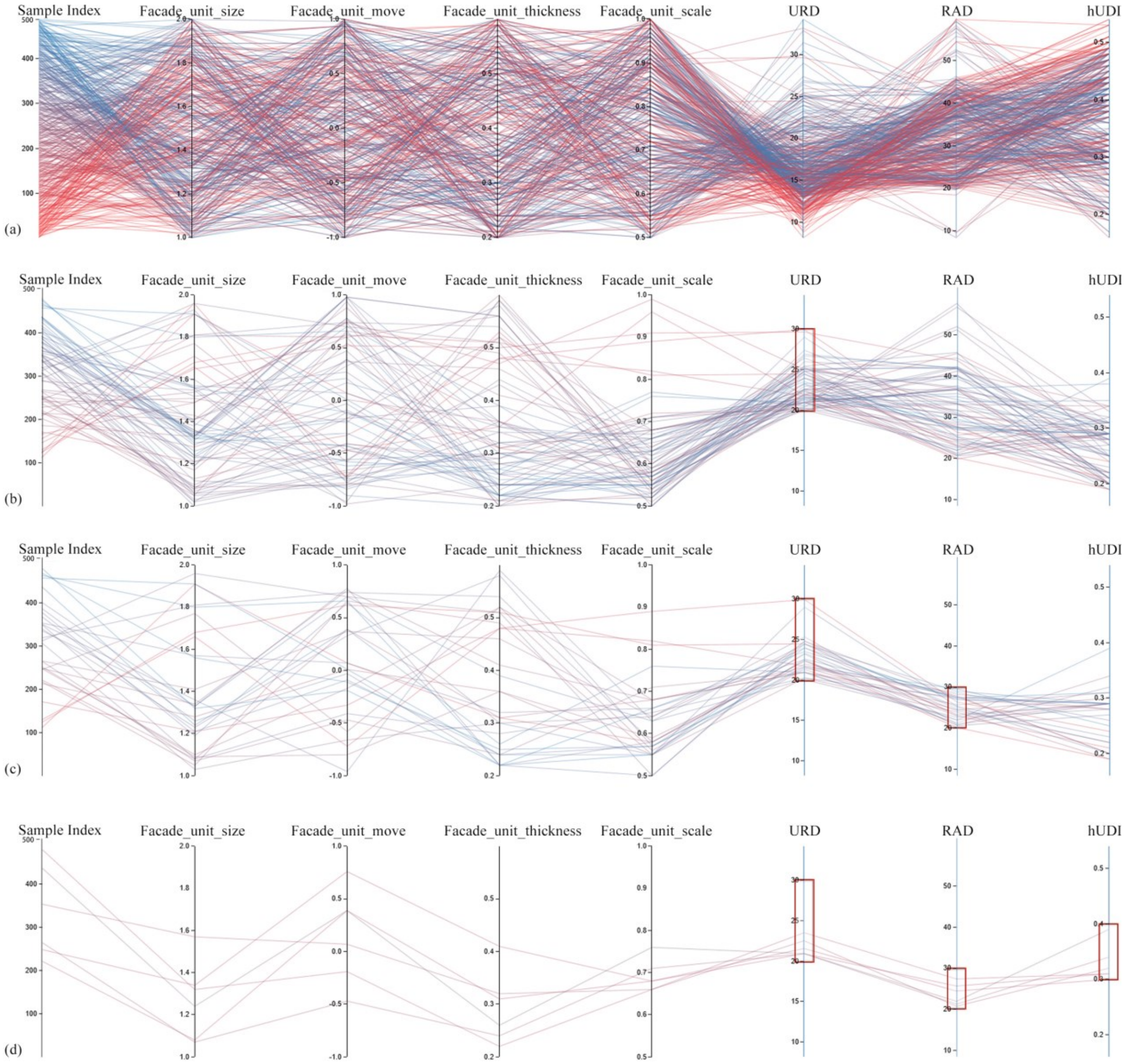


Figure 3.16: Simulation outcomes regarding the daylight and thermal performance of office buildings, encompassing a comprehensive range of results from 500 iterations (a), optimal design scenarios for URD (b), optimal design scenarios for URD & RAD (c), and optimal design scenarios for URD & RAD & hUDI (d) (Source : Yan, H. et al., 2022)

3.4 Bibliometric analysis of related works using Vos Viewer analysis

3.4.1 VosViewer Overview

The examination of strategies for controlling daylight encompassed an investigation into the shifts in the degree of association among significant terms present in research article titles, abstracts, and keywords. For establishing a baseline, special attention was directed towards the year 2010, which represented a pivotal phase marked by widespread adoption of technological advancements in lighting and building control systems. This temporal juncture played a crucial role in comprehending the progression of these strategies over time. Initially, a compilation of keywords was amassed, encompassing those provided by authors of each research paper within the designated timeframe. Yet, given the substantial potential variation in keyword formulation among authors, a fresh set of terms was introduced to categorize these keywords. Each term within this set corresponds to a distinct keyword category and is denoted as an "item" using the terminology of VOSviewer. The ensuing analysis was centered on gauging the strength of correlation between these items. In order to depict the interconnections among the items, the VOSviewer tool (version 1.6.19) was employed. The identical methodology employed by VOSviewer was applied, entailing the utilization of a similarity measure to quantify the degree of correlation between two items (see to Figure 3.2).

VOSviewer stands as a potent software tool, offering invaluable utility to researchers in the bibliometrics domain. It presents advanced functionalities tailored to visualize and scrutinize bibliometric networks, equipping users with a proficient means to navigate and chart scientific literature. Through the examination of keyword co-occurrences, author interactions, and other entities within a specified dataset, VOSviewer aids researchers in uncovering pivotal subjects, recognizing nascent research trends, and comprehending the intricate interrelations between distinct entities. VOSviewer boasts an array of visualization methods, including co-occurrence maps, term maps, and network maps, empowering researchers with profound insights into the structure and fluidity of domains within scientific knowledge (Moustakas, L., 2022).These visual depictions facilitate the discernment of critical research arenas, the illustration of collaborative networks among authors, and the tracing of the developmental trajectory of research themes over time. By furnishing an intuitive portrayal of intricate bibliometric data, VOSviewer simplifies the task of achieving a comprehensive grasp of the research landscape. Its capabilities have led to its widespread integration into bibliometric and scientometric inquiries. VOSviewer lends support to data-driven analyses, arming researchers with essential tools to navigate and interpret substantial volumes of scholarly literature. Beyond this, VOSviewer occupies a pivotal role in the research evaluation process, assisting institutions and funding bodies in informed decision-making and the formulation of effective research strategies. Through harnessing insights gleaned from VOSviewer analyses, researchers can actively contribute to the progression of knowledge and innovation within their respective fields (Moustakas, L., 2022).

3.4.2 The Most Cited Documents ranking

Regarding individual documents, the extensively referenced publications encompass a diverse array of keywords and domains relevant to the subject matter of research papers concerning the evaluation and enhancement of daylight performance. As follows the Table 3.1 illustrates the foremost fifteen documents with the highest citation counts.

Table 3.1: Examples of the most cited Journal paper on "Daylight performance" based on total citations and key words parameters (Source: Author, 2023)

Document Title	Authors	Publisher	Total Citations	Total link strength	References
evaluation methods and development of a new glare prediction model for daylight environments with the use	wienold j., christoffersen j.	Energy build.	1115	39	Wienold, J., & Christoffersen, J. (2006)
dynamic daylight performance metrics for sustainable building design	reinhart c.f., mardaljevic j., rogers z.	leukos	1054	52	Reinhart, C. F., et al. (2006)
useful daylight illuminances: a replacement for daylight factors	nabil a., mardaljevic j.	Energy and buildings	1016	20	Nabil, A., & Mardaljevic, J. (2006).
passive performance and building form: an optimization framework for early-stage design support	konis k., gamas a., kensek k.	sol. energy	233	12	Konis, K. et al., (2016)
photometry and assessment of bidirectional photometric properties of complex fenestration systems	Andersen m., de boer j.	energy build	104	89	Andersen, M. et al., (2006)
The parametric based optimization framework daylighting and energy performance in residential buildings in hot arid zone	A Toutou, M Fikry, W Mohamed	Alexandria engineering journal	83	67	Toutou, A. Et al., . (2018).
Simple tool to evaluate the impact of daylight on building energy consumption	Hviid, C.A., Nielsen, T.R., Svendsen, S.	Solar Energy	69	87	Hviid, C. A. Et al., (2008).
analysis of the daylight performance of a glazing system with parallel slat transparent insulation material	sun y., wu y., wilson r.	energy build	44	67	Sun, Y. et al., (2017)
FAST energy and daylight optimization of an office with fixed and movable shading devices	Manzan, M., Clarich, A.	Building and Environment,	40	23	Manzan, M. et al., (2017)
Multi-objective optimization of thermochromic glazing based on daylight and energy performance evaluation	Hong, F Shi, S Wang, X Yang, Y Yang	Building Simulation	31	13	Hong, X. et al., (2021)

The document that has garnered the highest number of citations is authored by Wienold et al. (2006). The most cited first article is titled "evaluation methods and development of a new glare prediction model for daylight environments with the use". The article has been cited 1115 times since its appearance in 2006 (see Figure 3.17). In the second ranking, the research article authored by Reinhart, Mardaljevic, and Rogers (2006) under the title "Dynamic Metrics for Assessing Daylight Performance in Sustainable Building Design" addresses a fundamental component of sustainable architectural planning: the effectiveness of natural lighting. The authors introduce the innovative concept of dynamic metrics for evaluating the performance of daylight, emphasizing the necessity of appraising light conditions within structures over extended durations, as opposed to static evaluations. The paper underscores the limitations of conventional daylight metrics, which often disregard the time-based and dynamic aspects of natural light availability and distribution within built environments. The authors suggest a more comprehensive methodology that encompasses the evolving illumination conditions throughout the day and across various seasons. According to underscoring the dynamic essence of natural light, the authors contribute to a more comprehensive comprehension of its interaction with constructed surroundings. This approach holds the potential to inform superior design choices, enhancing not only visual comfort but also energy efficiency and the well-being of occupants. The significance of this paper lies in its advocacy for a transformative shift in how the effectiveness of daylight is gauged and incorporated into sustainable architectural design. It urges architects, designers, and researchers to contemplate the dynamic attributes of natural light, fostering more optimized and ecologically responsible architectural solutions. The methodologies and insights presented within this paper are likely to have a long-lasting influence on the realm of sustainable architecture, persistently shaping the strategies designers adopt when integrating daylight considerations into building designs.

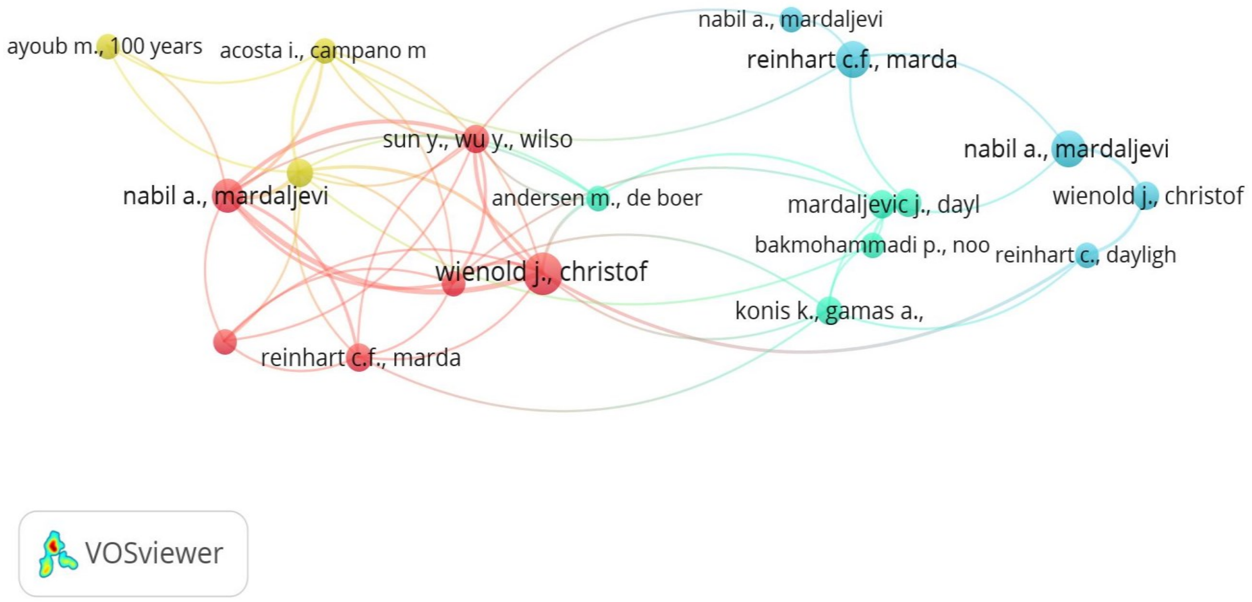


Figure 3.17: Bibliometric analysis of publications on Daylight performance topic by number of citations. The size of each node (circle) indicates the number of documents associated with an author. Lines represent co-occurrence between two authors and appear when authors co-occur at least once (Source: Author, 2023)

The bibliometric investigation aimed to delve into the scholarly influence and impact of research articles pertaining to the domain of daylight performance. The quantification of citations, a pivotal gauge of research's importance and acknowledgment, assumed the role of the primary metric for assessing each publication's significance. Through an examination of citation dispersion across these articles, valuable discernments emerged regarding the prominence of specific works. Articles with a substantial citation count reflect a robust resonance within the research community, indicative of groundbreaking contributions or pioneering insights. Conversely, articles with fewer citations may signify areas with restricted impact or research in its early stages. Moreover, the analysis transcended mere citation tallies to encompass temporal citation patterns. This temporal dimension furnished a deeper comprehension of the articles' enduring relevance and durability. Publications consistently amassing citations over an extended period may symbolize abiding concepts or principles that continue to shape the realm of daylight performance. Conversely, articles experiencing a surge in citations followed by a decline might underscore the sway of emerging trends or the rapid evolution of specific research avenues.

Through the execution of this bibliometric scrutiny, a holistic viewpoint of the daylight performance research landscape was attained. The varying magnitudes of citations, interwoven with temporal trends, facilitated the identification of seminal contributions, emerging focal points, and the evolving dynamics within scholarly dialogues. These insights not only contribute to charting the course of research but also offer assistance to researchers, practitioners, and policymakers in recognizing the pivotal roles that mold advancements in the comprehension and practice of daylight performance.

3.4.3 The Most Cited Authors bibliographic analysis

Table 3.2 displays a depiction of the leading 15 authors who have demonstrated remarkable productivity in terms of document output, as well as the top 15 authors who have garnered substantial citation counts. This evaluation of rankings was executed utilizing a full counting approach within VOSViewer, wherein each document or citation is accorded equal significance, regardless of the total author count within a given document. The citation analysis was conducted without imposing a minimum threshold for the number of documents. Notably, Mardaljevic emerges as the foremost highly cited author in the domain of Daylight performance from the period spanning 2014 to 2023, as indicated by the tally of citations (see Figure 3.18).

Table 3.2: Top 15 most cited authors on Daylight performance topic from (2014-2023) (Source: Author, 2023)

Ranking	Authors	Total Citations	Total link strength
01	Mardaljevic j.	765	5154
02	Reinhart c.f.	135	4257
03	Andersen m.	102	3831
04	Wienold j.	91	3460
05	Sun y.	61	2578
06	Nabil a.	52	1760
07	Ward g.	46	2174
08	Mcneil a.	44	1944
09	Su y.	42	1586
10	Norton b.	26	1123
11	Walkenhorst o.	23	849
12	Boubekri m.	21	576
13	Pellegrino a.	20	924
14	Tregenza p.r.	18	674
15	lee e. S	18	717

Utilizing VOSViewer, a co-authorship analysis was conducted, and clusters were formed through the application of the association strength technique. Inclusion criteria encompassed authors with no fewer than five documents, resulting in a combined count of 211 authors. Among these, only 64 authors are prominently showcased within the interconnected central clusters (in blue, red, green, yellow, and pink hues) as illustrated in Figure 3.18. These clusters delineate groups of authors closely linked in their collaborations, with authors frequently appearing together tending to be positioned in proximity to one another within the visualization.

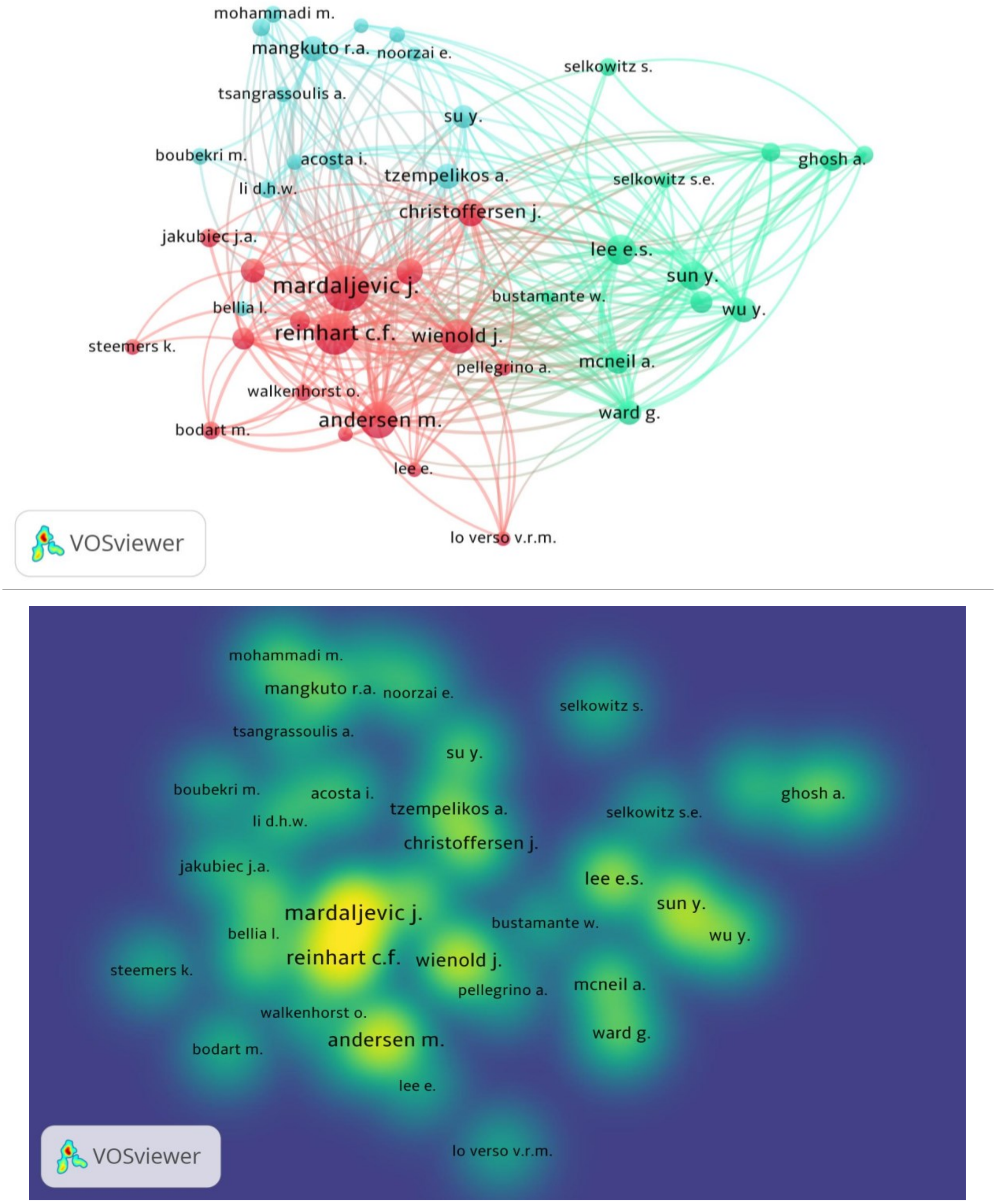


Figure 3.18: Co-author network for "Daylight performance." The size of each node (circle) indicates the number of documents associated with an author. Lines represent co-occurrence between two authors and appear when authors co-occur at least once
(Source: Author, 2023)

3.4.4 Keywords Occurrence network for "Daylight performance topic"

Through the application of Author Keyword analysis within VOSViewer, a total of 20,124 keywords were identified. The leading 17 keywords, arranged based on their overall occurrences and depicted in Figure 3.19, encompass a blend of terms originating from diverse fields such as Engineering, Architecture, Built Environment, and Material Science, among others.

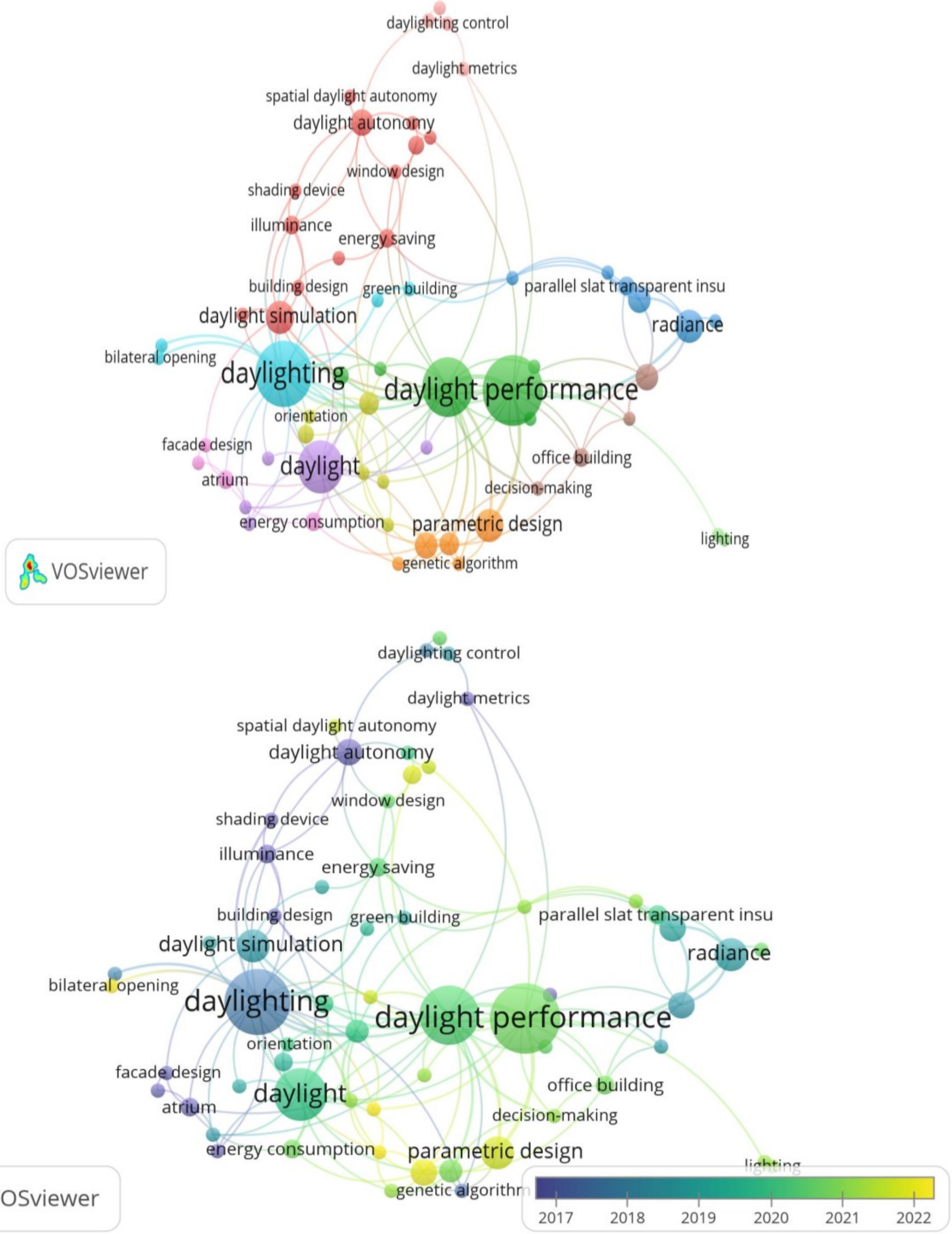


Figure 3.19: Author keyword co-occurrence network for "Daylight performance." The size of each node (circle) indicates the number of documents associated with an author. Lines represent co-occurrence between two authors and appear when authors co-occur at least once (Source: Author, 2023)

Employing VOSViewer's co-occurrence analysis, author keywords were graphed and interconnected visually. To streamline the visualization to a more manageable set of keywords, only terms with 17 occurrences were retained, resulting in a sum of 41 terms divided into three clusters (designated by green, red, and blue in Figure 3.19). Clusters signify groups of closely interrelated nodes, and terms that frequently co-occur tend to be positioned in closer proximity within the visualization. These clusters were shaped using the association strength method and, to streamline analysis and reduce smaller clusters, a stipulation was set requiring clusters to encompass a minimum of 12 items. Subsequent sections provide a narrative overview of significant themes and trends encapsulated within each cluster. It's important to note that these summaries serve as illustrative depictions and are not all-encompassing. Additionally, numerous articles incorporate keywords associated with multiple clusters, allowing for debate regarding the thematic cluster that best aligns with individual articles.

3.6 Conclusion

In this chapter, we introduced the multi-objective genetic algorithms approach to optimization, which has recently gained popularity in the optimization field. Firstly, we discussed fundamental concepts such as multi-objective optimizations, and genetic algorithms as the primary evolutionary computational model for optimization. Subsequently, we provided a summary, review, and investigation of current studies that employ the multi-objective genetic algorithms approach. These studies primarily focused on optimizing the energy balance of urban forms, energy demand of buildings, and energy demand, daylighting, and thermal comfort optimization of buildings. Through analyzing these studies, we gained insights into the comprehensive workflow of the multi-objective optimization approach. This understanding will prove valuable when developing a multi-objective optimization workflow to address the complex task of designing a courtyard in a semi-arid climate.

It have demonstrated through a systematic bibliometric study the state of the art on "Parametric Based Multi-Objective Optimization for Daylight and Energy Performance: Review of Recent Studies." What is presented is a collection of ideas and solutions proposed by various research papers in the literature over the past decade. It has been shown that the solutions vary depending on time, climate, and latitude.

More broadly, recent studies do not analyze the influence of each parameter independently. Instead, they adopt an approach that takes into account the interactions between parameters. The development of research tools, particularly after the emergence of parametric analysis and optimization using advanced algorithms, has made it possible to study the impact of multiple factors and multiple objectives. The publication trend shows a significant number of papers on the subject since 2014. The recent increase in publications on this topic aligns with global efforts to achieve sustainable energy transition, which is a major focus of government programs in most countries worldwide. Despite the differences in objectives, research questions, domains, and case studies represented in the analyzed corpus, the energy aspect remains the central concept on which this research field is built. Thematic analysis revealed that, except for a few modest attempts, few studies have investigated the parametric approach and optimization. The advantage is often given to the two extreme cases: maximizing daylighting due to high demand for clean solar energy in cold climates or minimizing solar gains in hot and arid climates. In a semi-arid climate, research needs to consider both opposing cases: maximizing solar energy in winter and protecting the building envelope from undesirable solar radiation in summer. This duality poses a significant challenge for designers and requires effective tools to address it.

PART II: PRACTICAL PART

METHODOLOGICAL FRAMEWORK, ASSESSMENT, AND OPTIMIZATION

CHAPTER 4

THE EMPIRICAL STUDY AND DATA MONITORING

4.1. Introduction

Throughout history, architecture and climate have shared an essential connection. This connection holds particular importance in the realm of daylighting, as the presence of sunlight and factors related to thermal comfort are predominantly influenced by the climate. In southern Algeria where the pilot study takes place, it is characterized by a challenging hot and dry climate, where the majority of the year experiences sunny and clear skies, infrequent rainfall, desert winds, and extremely low humidity. The high temperature poses a significant challenge for designers due to intense solar radiation. During the summer, temperatures in this region can exceed 40°C. As a result, there is a substantial demand for cooling energy in buildings, and heat gain through openings plays a significant role in the cooling load, contributing to the overall energy demand (Gut, P. and Ackerknecht, D., 1993). Among different building types, hospital buildings have the highest Energy Use Intensity (EUI). Unfortunately, there is a notable lack of studies focusing on architectural efforts to enhance indoor daylighting and energy efficiency in healthcare facilities in Algeria. Consequently, it is imperative to address the issues of indoor environmental dissatisfaction in these crucial buildings. This study aims to develop more sustainable patient room designs specifically tailored to the unique conditions of hot and dry locations.

In this context, this chapter focuses on developing the methodological framework and conducting empirical fieldwork for on-site measurements. The chapter begins by briefly describing the location and the existing health buildings in Biskra city. The purpose of this section is to present the range of health buildings in Biskra and choose a suitable hospital for the pilot study. Once the hospitals were selected, measurements of daylight levels were conducted. The objective was to obtain detailed quantitative evaluations of natural lighting in the patient rooms of the Pediatric ward at Hakim Sadaan Hospital. The chapter also outlines the protocol for measurements, data collection, and result analysis. Thus, this empirical section aims to identify problems and propose optimal solutions to address them.

4.2. Pilot study description

4.2.1. Location and climatic conditions of the study context

This research was conducted in Biskra, it is a Saharan city located in the southeast of Algeria (see Figure 4.1), with geographical coordinates of 34°51′N 5°44′E / 34.850°N 5.733°E. This city is characterized by a hot and dry climate, exhibiting significant temperature fluctuations between day and night as well as across seasons. According to the International Köppen climate classification, Biskra falls within the BWh zone (Lakhdari K., 2021; Semahi et al., 2019; Mahaya, C., 2022).

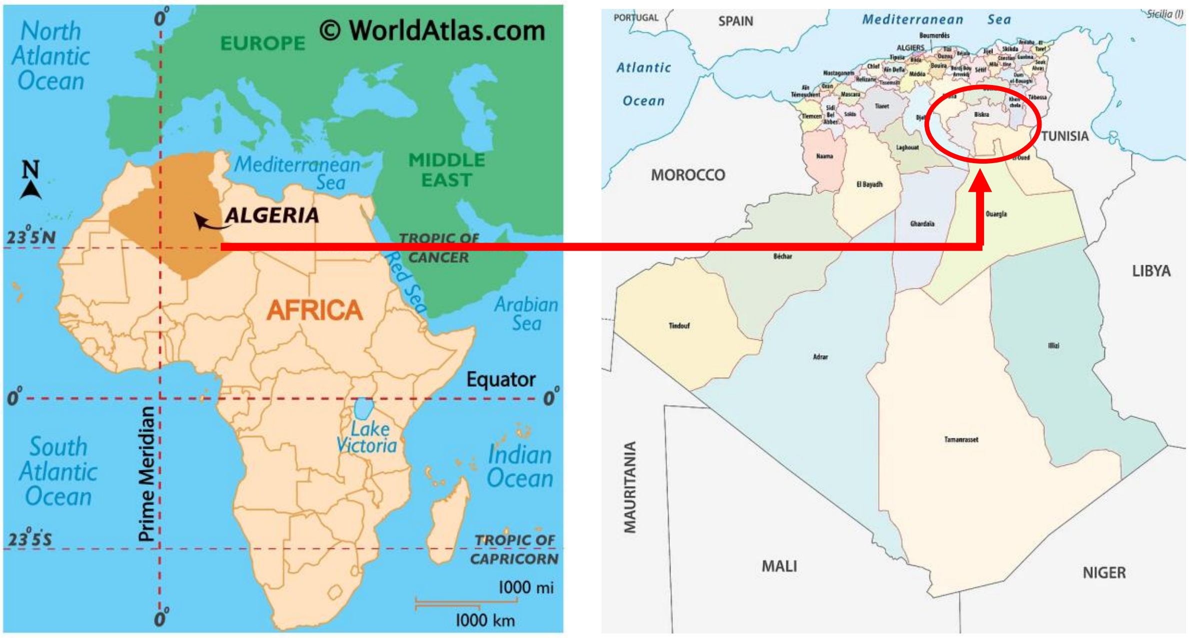


Figure 4.1: The geographical map of Algeria indicating the location of Biskra city (Source: www.worldatlas.com/maps/algeria)

The region experiences a clear sky, arid conditions, abundant sunshine, and infrequent rainfall, resulting in low humidity (Khadraoui, M. A., 2019; Khadraoui, M.A., et al., 2019). The last version of the Typical Meteorological weather data for Biskra was obtained from the Climate One Building website (epw) hourly weather data files (Meteonorm V.8). Figure 1 illustrates that the city of Biskra reaches extremely high average summer temperatures, exceeding 40°C in July, with nighttime temperatures dropping to around 20°C (Gut, P. and Ackerknecht, D., 1993; Chen, Y. et al., 2014; Lakhdari K. et al., 2021). On the other hand, the average winter temperature ranges from 8°C to 15°C in January, marking the coldest month. Hot climates present challenges related to uniform daylight distribution and intense heat gain. The buildings in Biskra city are directly exposed to solar radiation, as depicted in Figure 4.2 and Figure 4.3. Consequently, this can lead to visual discomfort and excessive heat accumulation, as observed in meteorological data over the year. For more details on the climatic characteristics of the city of Biskra refer to (Appendix A).

4.2.2. Types of health buildings that exist in Biskra city

There is a wide range of health facilities that serve distinct purposes and deliver specific healthcare services. Some commonly found types of health facilities include (Staff Writers, 2023; Brianna F., 2018; Besbas, Y., 2019):

- Hospitals: These are the main and large medical establishments that offer a broad array of medical services, including emergency care, surgeries, specialized treatments, and inpatient care.
- Clinics: Clinics are smaller healthcare facilities that provide outpatient medical services. They often specialize in specific areas such as primary care, pediatrics, or women's health.
- Medical Centers: Medical centers are comprehensive healthcare facilities that provide various services, including outpatient care, diagnostic testing, specialized treatments, and medical consultations.
- Nursing Homes: Nursing homes, also known as skilled nursing facilities, provide long-term care and support for individuals who require specialized medical attention due to chronic illnesses, disabilities, or age-related conditions.
- Pharmacies and Drug Stores: These establishments offer prescription medications, over-the-counter drugs, and other pharmaceutical products. Pharmacists also provide guidance and counseling on medication usage and potential interactions.
- Rehabilitation Centers: Rehabilitation centers focus on delivering specialized therapies and treatments to individuals recovering from surgeries, injuries, or chronic conditions. They offer services such as physical therapy, occupational therapy, speech therapy, and other forms of rehabilitation.
- Diagnostic Centers: Diagnostic centers are equipped with advanced medical technology and equipment to perform diagnostic tests and medical imaging procedures like X-rays, CT scans, MRIs, and laboratory tests.
- Specialty Clinics: Specialty clinics cater to specific medical specialties such as cardiology, dermatology, orthopedics, oncology, or mental health. They provide specialized care and treatments related to their respective fields.
- Urgent Care Centers: Urgent care centers provide immediate medical care for non-life-threatening conditions that require prompt attention but do not necessitate emergency room services.

These examples highlight the diverse range of health facilities available to meet the varied healthcare needs of individuals and communities. As seen in Figure 4.2, illustrates a sample of existing health buildings in the city of Biskra.

Figure 4.2: Sample of existing health buildings in the city of Biskra

(Source: Author, 2021; www.dsp-biskra.dz)

4.2.3. Selection and criteria used to select the study object

4.2.3.1. Criteria used to select Hakim Sadaane Hospital

In selecting a hospital case study for research, several factors and criteria are typically considered. Firstly, Hospitals usually function as central focal points for delivering healthcare, where patients receive comprehensive medical care, consultations, and treatments. They frequently feature specialized divisions or units devoted to specific medical fields, including cardiology, orthopedics, oncology, pediatrics, and others. Moreover, hospitals play a critical role in advancing medical research, facilitating education, and providing training opportunities for healthcare professionals. The primary objective of a hospital is to deliver top-notch medical care, enhance patient well-being, and enhance health outcomes (Crowe, S., 2011). These institutions serve as indispensable entities within the healthcare system, offering a broad array of services to cater to the diverse healthcare needs of individuals and communities. Additionally, the hospital had to have a pediatric ward, as the focus of the study was on daylight quality in pediatric healthcare environments. This criterion ensured that the research could directly examine the impact of daylight on young patients. Then, other several factors were considered in the selection to ensure the relevance and the suitability including; one important aspect was the geographical location, which needed to align with the research focus (Rashid, Y., 2019). Factors such as climate, demographic characteristics, and the context of the healthcare system were taken into account to ensure the chosen hospital was situated in a suitable area. The specialization or focus area of the hospital was another criterion. Hospitals specializing in specific fields such as pediatrics, cardiology, oncology, or other relevant areas were given consideration, depending on the research topic. The availability of necessary data and information for the research was a crucial factor. The selected hospital needed to have accessible and reliable data related to the research objectives, allowing for meaningful analysis and findings. The cooperation and accessibility of the hospital administration and staff were assessed as well. It was important that the selected hospital demonstrated willingness to participate in the research and provide the necessary access for data collection and analysis.

Overall, the selection criteria were carefully designed to ensure that the chosen hospital case study would have valuable insights and make a meaningful contribution to the research objectives.

4.2.3.2. Criteria used to select Pediatric Ward in Hakim Sadaane Hospital

The choice of the pediatric ward as a focal point in daylight quality studies is driven by several compelling reasons. These key factors elucidate the significance of studying daylight in this particular healthcare setting including firstly; Due to the Vulnerable Patient Population; Pediatric patients, comprising infants, children, and adolescents, exhibit heightened vulnerability and sensitivity to their surroundings. Extensive research has demonstrated that exposure to natural daylight can positively impact their well-being, comfort, and recovery (Joon, H.C., 2005; Volf Carlo, 2013; 2016; Hellinga; Moscoso, C. P., 2016). Consequently, investigating the influence of daylight in the pediatric ward can facilitate advancements in healing practices and enhance the overall experience of these young patients. Moreover, other factor which is the impact of healing and Well-being; Daylight has been associated with numerous health benefits, including improved mood, reduced stress levels, and expedited recovery times. Concentrating on the pediatric ward enables researchers to explore how the presence and quality of daylight contribute to the healing process and the overall well-being of young patients (Volf Carlo, 2013; Moscoso, C. P., 2016; Hellinga, HY., 2013; Mohamedali, Ahmed, 2017). In addition, effect on development and Growth: Children are in critical developmental stages, and exposure to natural daylight plays a pivotal role in their cognitive, visual, and physical growth. Toward studying daylight quality in the pediatric ward, researchers can gain insights into how adequate daylight exposure supports optimal development and growth in young patients. Furthermore, another criteria, effect on comfort and Environmental Quality: with creating a comfortable and pleasant environment for pediatric patients holds significant importance within healthcare settings. Daylight possesses the potential to enhance visual aesthetics, establish a connection with the outdoor environment, and improve the overall environmental quality of the pediatric ward. Through an exploration of daylight quality, researchers can identify strategies to optimize the comfort and experience of young patients and their families (Mohamedali, Ahmed, 2017). Lastly, influence on design and Architectural Considerations: Findings derived from studies on daylight quality in the pediatric ward can inform future design and architectural decisions for healthcare facilities. Understanding the impact of daylight on pediatric patient spaces empowers architects and designers to develop environments that promote healing, well-being, and positive experiences for young patients (Alzoubi, H. et al., 2010; Alzoubi, H. et al., 2015).

In summary, examining daylight quality in the pediatric ward is of paramount importance to ensure that healthcare environments are adapted to meet the specific needs of pediatric patients, thereby fostering their healing, development, and overall well-being.

4.2.4. Building case study description (Dr. Hakim Sadaane Hospital)

4.2.4.1. Brief history of the hospital

Over the past few decades, since the start of Algeria's colonization, numerous religious congregations accompanied the African army with the purpose of evangelizing the African communities. Alongside their efforts, they offered complimentary medical services to underprivileged "natives" in hospitals overseen by the White Fathers. These "Catholic hospitals" played a role in promoting Christianity, yet faced challenges due to the deeply entrenched presence of Islam among the populace. However, in the realm of healthcare, they acted as catalysts for introducing modern medicine, even though their endeavors to convert Muslim populations to Christianity or embrace "Western civilization" were not successful (Medjahed, Y. and L. Abid., 2022).

The Lavigerie Hospital as seen in the Figure 4.3, currently known as Dr. Saadane Hospital, located in Biskra, was established in the same year as Aurès Hospital (1895). Its construction was commissioned by the General Government, and the management responsibilities were entrusted to the religious order of Notre-Dame d'Afrique. The endeavor of serving the Arab populations in the Sahara region began in 1856 when priests settled in Laghouat. Subsequently, in 1859, the Sisters of St. Vincent de Paul arrived to provide healthcare services to the sick. Following the tragic loss of three priests, they withdrew until the revival of missionary efforts in the 1890s. (Medjahed, Y. and L. Abid., 2022).

Figure 4.3: hôpital Lavigerie 1950 (Hakim Sadaane hospital)

(Source: www.vitaminedz.com/fr/Algerie/hopital-lavigerie-biskra)

4.2.4.2. Case study description

The Hakim Saadane hospital, as depicted in Figure 4.4, is positioned in the northeastern section of Biskra city. The Dr. Saadane Public Hospital (EPH) is located in the center of a palm grove, covering an area of 4 hectares. Currently, it has a technical capacity of 204 beds (organized into 192 beds) and caters to the healthcare needs of the Biskra province population. The Dr. Saadane Hospital is a Public non-University Hospital Establishment (EPH) which consists of six Hospitalization wards: Cardiology, Pneumo-phthisiology, Oncology, Pediatrics, Psychiatry, and Internal Medicine (see Table 4.1) (DSP Biskra, 2022).

Figure 4.4: Exterior and interiors photos of Dr. Hakim Sadaane hospital

(Source: Author, 2020)

Table 4.1: Hospital departments and their units
(Source: www.dsp-biskra.dz)

Wards	Units Number	Technique Beds	Organized Beds
Internal Medicine	02 men and women	50	50
Cardiology	02 men and women	20	18
Pneumo-phthisiology	02 men and women	30	30
Oncology	02 men and women	14	14
Psychiatry	02 men and women	50	50
Pediatrics	01	40	30
Total beds		204	192

The hospital itself is an aged structure, featuring walls that are 0.50 meters thick and constructed with alveolar terracotta bricks. Additional information regarding the hospital building's construction materials can be found in Table 4.2 and Table 4.3 (DTR C 3-2, 1997; Besbas, Y. et al., 2018; Besbas, Y., 2019).

Table 4.2: Building construction materials of the hospital Hakim Sadaan – External and Internal wall (Source: Hakim Sadaane hospital, DTR C 3-2 1997 Documentation Technique Réglementaire du Ministère du Logement, Algérie)

	Parameters	Unit	Exterior plaster coating	Brick25-alveolar	Interior plaster coating
External wall	T	m	0.01	0.50	0.01
	λ	W/(m·K)	1.1533	0.31083	0.35111
	D	kg/m3	1700	720	1500
	C	J/(kg·K)	1000	794	1000
	U-value	(W/m2-K)	5.597	0.491	5.038
Internal wall	T	m	0.01	0.18	0.01
	λ	W/(m·K)	1.35111	0.31083	0.35111
	D	kg/m3	1500	720	1500
	C	J/(kg·K)	1000	794	1000
	U-value	(W/m2-K)	5.038	1.335	5.038

Table 4.3: Building construction materials of the hospital Hakim Sadaan – floor and Roof (Source: Hakim Sadaane hospital, DTR C 3-2 1997 Documentation Technique Réglementaire du Ministère du Logement, Algérie)

Parameter	Unit	Floor Materials			Roof Materials				
		Flooring	Floating slab	CALCl_T_N2	Sealing	Compression Slab	Steel	Air cavity	Interior Plaster coating
T	m	0.20	0.10	0.30	0.1	0.05	0.03	0.30	0.02
λ	W/(m·K)	1.714	1.755	1.230	1.75	1.755	44.4	$6.027e^{-2}$	0.351
D	kg/m3	2300	2300	1500	2300	2300	7800	1	1500
C	J/(kg·K)	700	920	800	920	920	510	1227	1000
U-value	(W/m2-K)	3.480	4.406	2.062	4.40	5.038	5.85	0.194	4.406

According to the Figure 4.5, the rooms chosen for the study are situated within the Pediatric Ward, which has a rectangular layout spanning two floors. The ground floor is arranged in an east-west axis, while the first floor is spread out in a north-south axis.

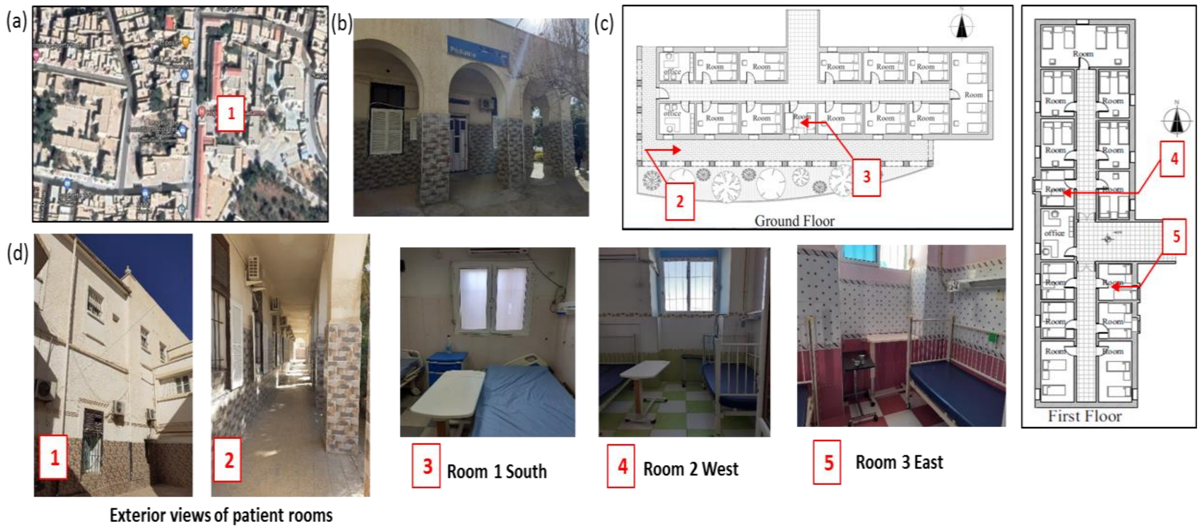


Figure 4.5: Illustration of Hakim Saadan Hospital (a) The location of the hospital; (b) A daytime photo for the hospital (Pediatric ward); (c) Floor plans of pediatric ward; (d) Photos of patient rooms, interior and exterior (Source: Author, 2021)

The initial room selected for analysis is on the ground floor and has a single opening facing the south. This opening consists of a window, covering 10% of the room's facade area, without any solar protection. The other two rooms selected for measurement are located on the first floor, with differing orientations; one faces east, while the other faces west (see Appendix B) (DSP Biskra, 2022).

4.3. The experimental campaign

4.3.1. On-site measurement protocol

During this empirical study, quantitative measurements were taken, following the description analysis of the case study and the selection of patient rooms based on their orientation and location, the objective was to assess the luminous conditions within the patient rooms in the Pediatric Ward in Dr. Hakim Sadaane Hospital. To accomplish this, measurements were conducted to evaluate the levels of interior illumination and at various locations, then take HDR photos with Camera CANON to measure Luminance levels.

To effectively measure the in situ evaluations of visual quality in the created lighting settings for each tested configuration, along with the photometric measurements observed by users in their visual fields and on their work surfaces during the execution of various visual tasks, we opted for utilizing appropriate measurement tools (see Figure 4.6).

Figure 4.6: On-site measurements protocol and taking HDR photos
(Source: Author, 2020)

- **<u>Illuminance measurements</u>:** In measurements, firstly a sample of hospital rooms of each orientation were selected in the Pediatric Ward. The measurements were defined depending on their configuration and location in order to collect data for the validation to verify and compare the daylight simulation performance of the base case model and the simulated values. As shown in Figure 4.7, the measurement of illuminance levels in the patient rooms was carried out regarding to a set of reference points which measured in a grid of (1.0 m by 1.0 m) of nine reference points, each point is located in the center of each square in the room at a height of 0.85 m. Conventionally, the reference points are defined using an orthogonal (imaginary) measurement grid covering the work plan. The grid is preferably square-shaped, and the number of points is calculated according to the standard (EN.2464-2).

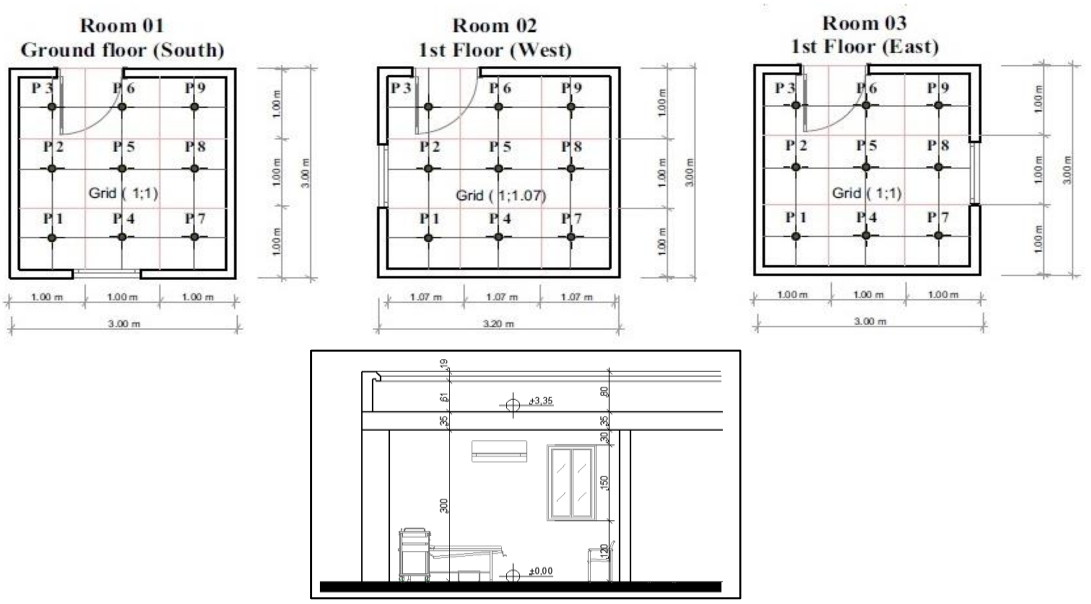
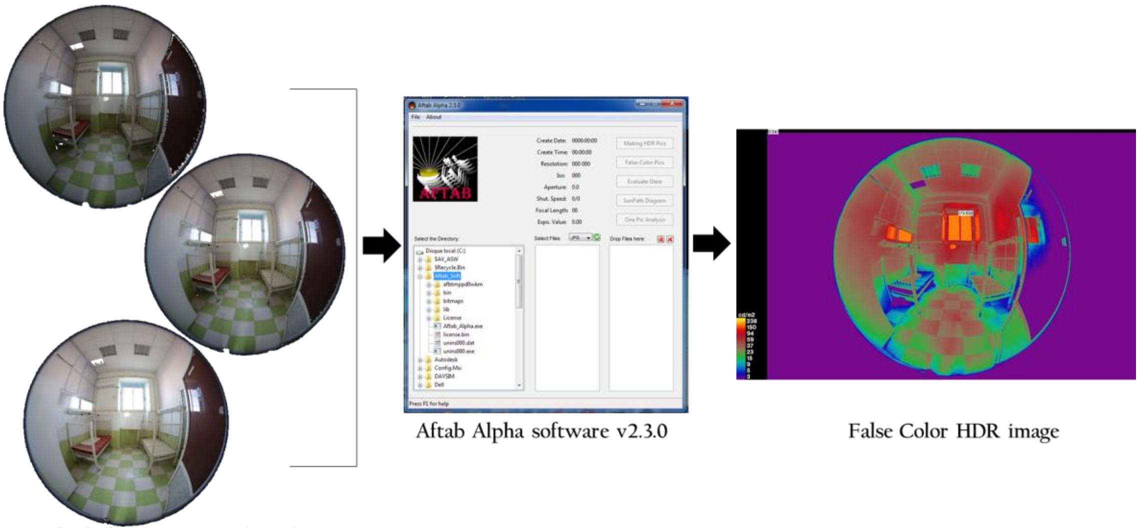


Figure 4.7: The plan (top) and section of patient rooms and placement of the reference points (Source: Author, 2020)

The illumination levels were assessed in the center of each square in the selected room. The on-site measurements occurred on three different days in three different months; December (12, 19 and 21 December 2020), March (04, 10 and 20 March 2021) and June (20, 21 and 24 June 2021) the winter, spring and summer period during 08:00 to 16:00. According to the CIE standards, the type of sky in these selected days of measurement was clear and sunny day.

- <u>**Luminance measurements:**</u> Typically, luminance levels are assessed by either employing a luminance meter tool or utilizing high dynamic range (HDR) imaging techniques along with a digital camera and luminance mapping analysis software (Andersen, A. et al., 2014). As a luminance meter was not available in this study, we opted to utilize an HDR image Camera for measuring the luminance levels in the patient rooms' case study. For the taking of the photos, a CANON EOS 1200D camera was used for the study, with a tripod (see Figure 4.6).

For these measurements the software (Aftab Alpha 2.3.0) was carried out to the production of Luminance map HDR False color images (see Figure 4.8).



high dynamic range (HDR)
Photos Fish-eye 180°

Aftab Alpha software v2.3.0

False Color HDR image

Figure 4.8: Image introducing process in Aftab Alpha software v2.3.0 / False Color HDR image Analysis (Source: Author, 2021)

First, the three images captured with a fish-eye lens at different exposures were introduced and merged them into a single High Dynamic Range (HDR) image using the software Alpha to cover a wide range of visible luminance. Then, the luminance values was calibrated in the software based on a measured real-world luminance value obtained from an actual visual field. Next, to develop the luminance distribution map of the visual fields, it was used the false-color images with calculation of values such as luminance on the ergorama, luminance on the panorama, average luminance, and maximum luminance. Finally, it can use this software also to calculated glare indices (CGI, UGR, DGI_P, and DGI) using the software's internal module, Evalglare.

4.3.2. Tools used for the measurements process

As seen in the Figure 4.9, the instrument used to measure the indoor illuminance is Testo 480 Probe Lux (accuracy: ±5 % ±10d). It is a versatile measurement tool equipped with intelligent digital probes that have built-in memory. This tool enables users to conveniently record, analyze, and document various climate and indoor air parameters using a single device. Moving on to the Fisheye Camera for measuring Luminance levels, below are the primary features of the CANON EOS 1200D (refer to Figure 4.9); Still image resolution of 18 MP with ability to capture Full HD 1080p movies, Compatibility with Canon EF and EF-S lenses, Equipped with a CMOS sensor, Powered by the Digit 4 image processor, Offers storage options of SD/SDHC/SDXC, Features a 9-point autofocus (AF) system and finally, Equipped with a 7.7cm (3.0") LCD display.

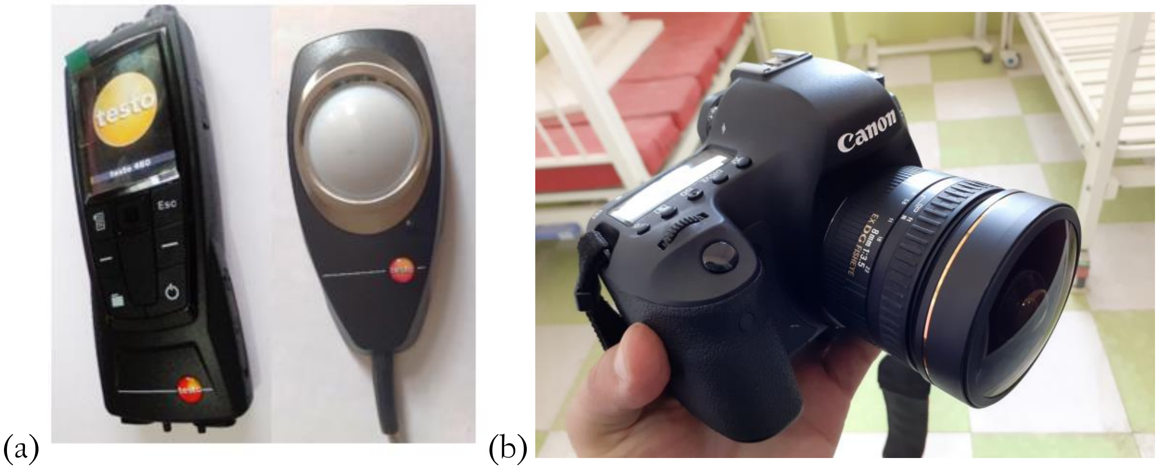


Figure 4.9: (a) Illuminance meter instrument (Testo 480 Probe Lux) (b) Camera Fisheye CANON EOS 1200D (Source: Author, 2021)

4.3.3. Results and analysis

4.3.3.1. Illuminance levels assessment:

Following the field measurements, a comparative analysis was conducted to compare the current situation with the recommended values (see Appedix C). The data collected for this analysis was processed using ORIGIN Lab Pro 9.6.5 software for graphs (see Figure 4.10) and MATLAB software (see Figure 4.11) for implementing Maps as follows in the below figures. As seen in Figure 4.10, it illustrates the distribution of illuminance levels in patient rooms during the hot season (June), spring (March) and the cold season (December). Previous studies have established that the suitable level of illumination in a hospital room should range from 100 to 300 lux for general, reading, and examination lighting (CIBSE, 2002; Alzoubi, H. et al., 2010; Alzoubi, H. et al., 2015; Sahar Diab et al., 2017).

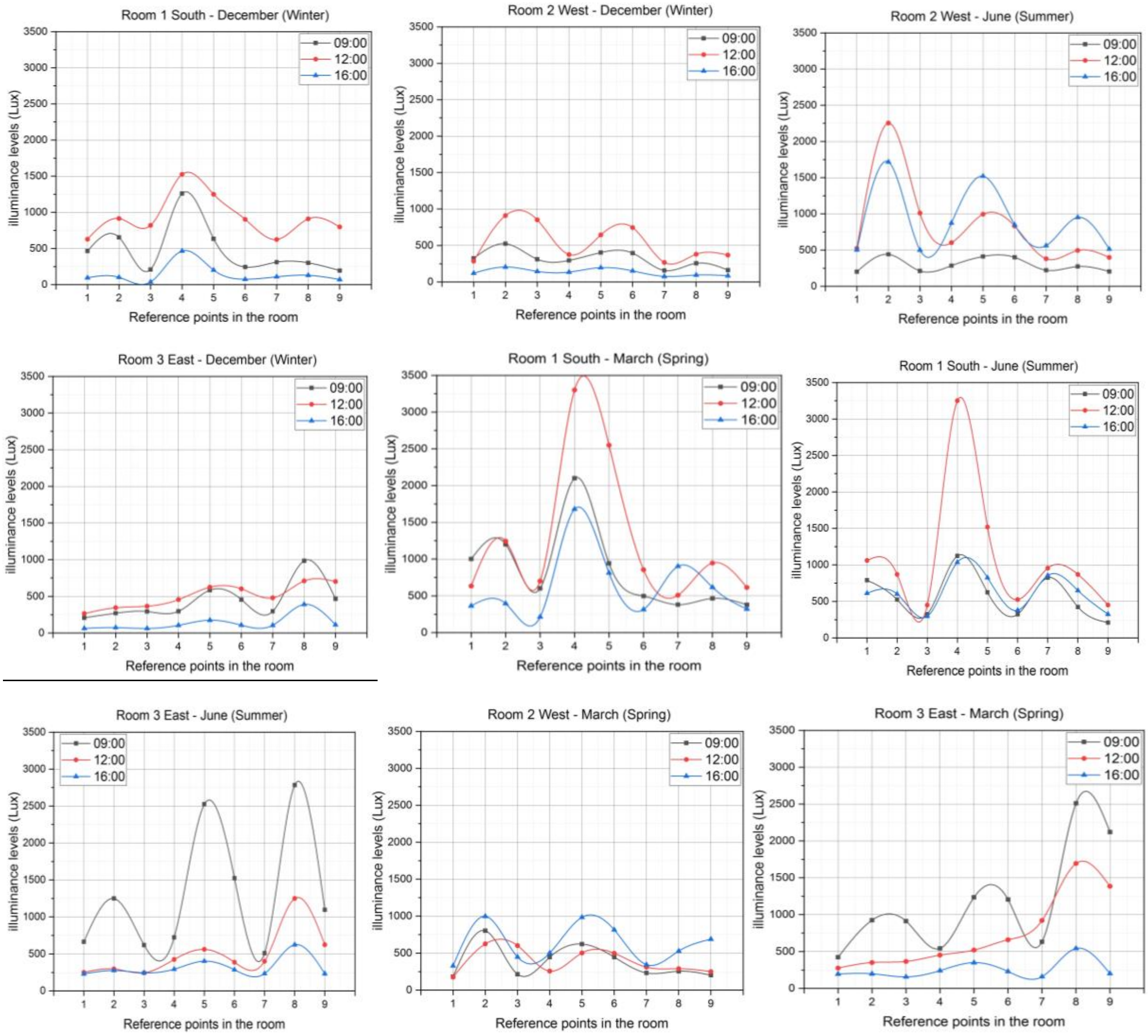


Figure 4.10: Illuminance Levels graphs in-patient rooms, on December, March and June "Clear sky" with ORIGIN Lab Pro 9.6.5 (Source: Author, 2022)

During the winter period, the measurements were taken over three days during the winter solstice; in December, the average illuminance level reaches approximately 1520 lux, with variations ranging from 63 lux to 1525 lux among the three rooms. This indicates an imbalance in lighting values concerning timing, orientation, and depth within each patient room. However, in June, the average illuminance level exceeds 3000 lux, with values ranging from 201 lux to 3250 lux. While, in March season the average illuminance level reaches approximately 2510 lux, with variations ranging from 156 lux to 2500 lux among the three rooms. These excessive illuminance levels are a result of the hot and arid climate Comparing the three rooms, the first room (south orientation) exhibits excessive illuminance levels in the morning hours (9 am-12 pm) at points 4-5, in contrast to the other rooms (east and west). Similarly, the west-oriented room experiences high illuminance levels (over 2000 lux) at points 2 and 3 during summer and spring, while in winter, the levels range from 300 to 900 lux. On the other hand, in the east-oriented room (room 3), the average illuminance level in December remains within the recommended range (100-300 lux) at points 1-7. However, in June, the illuminance level can reach around 2785 lux, particularly at point 8 in the morning, indicating the impact of time, location and orientation.

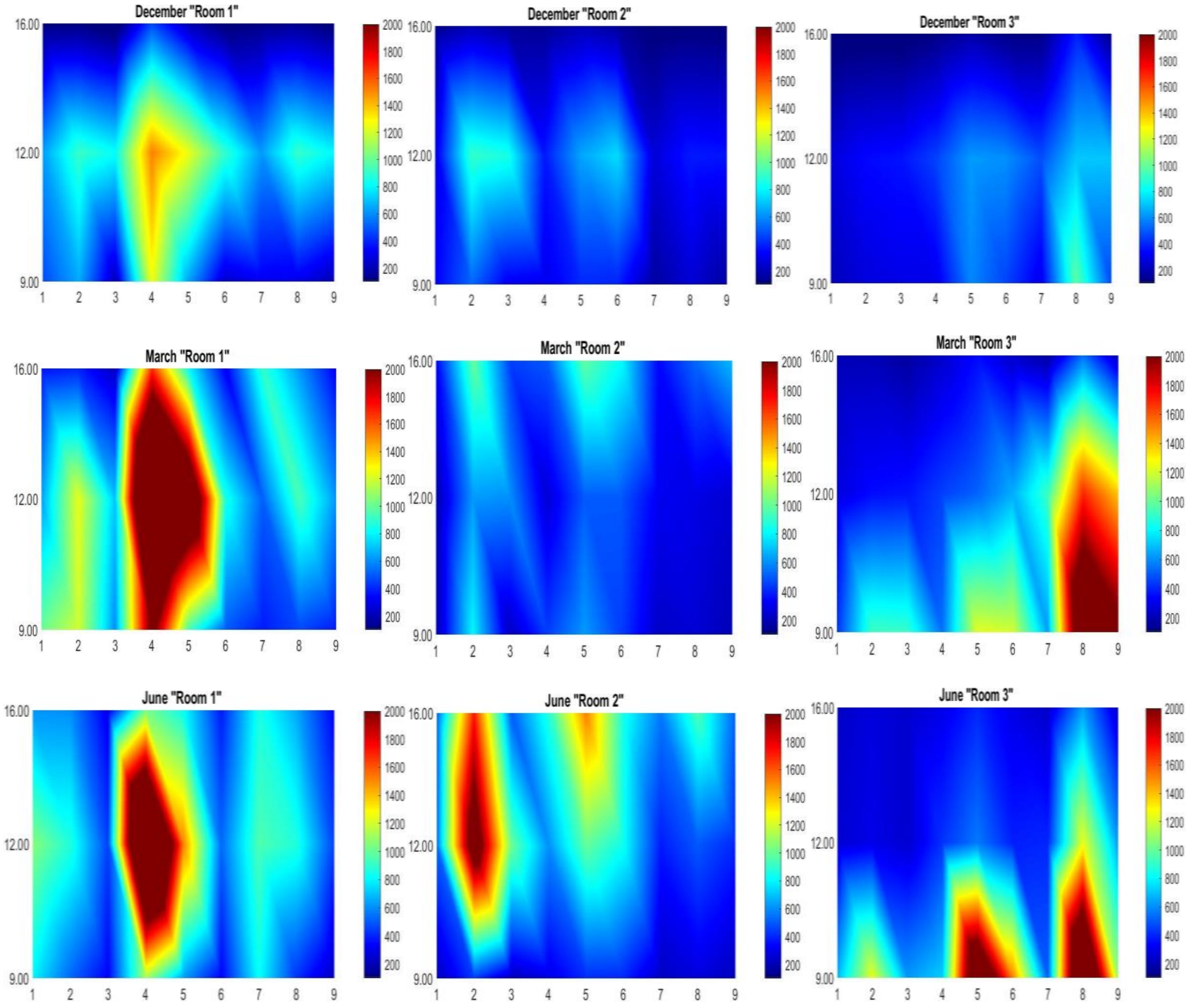


Figure 4.11: Maps of Illuminance Levels in-patient rooms, on December, March and June "Clear sky" (Source: Author, 2022)

The findings from the illuminance measurements reveal that the total illuminance level in the morning is higher than the standard levels for the nearest points to the openings but lower than the recommended values in the afternoon for the deeper parts of the space. The patient rooms facing south and west in the pediatric ward exhibit extremely high illuminance levels, which can negatively impact the health of patients and create exhausting conditions with overheating and glare sensation.

4.3.3.2. Luminance assessment

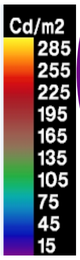
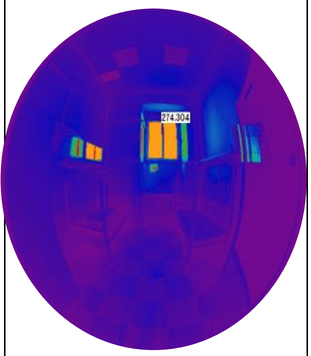
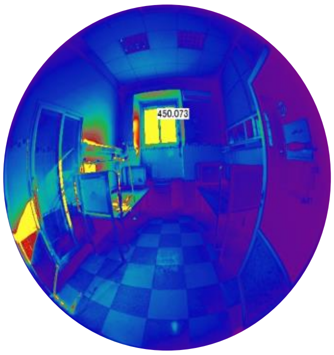
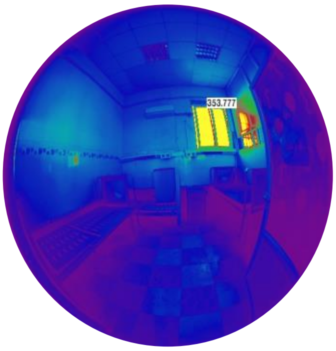
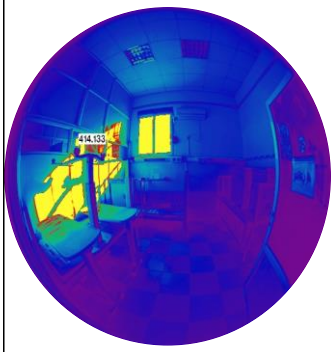
Table 4.4 shows the HDR images and falsecolor images of luminance values in the patient rooms in the Pediatric Ward for different times over the day (15/03/2021); at three diferent times; 9 PM, 12AM and 4 PM and in two different orientations East and West of the patient rooms in the hospital. The analysis of HDR False color images was carried out to illustrate the distribution of luminance values and the variations in color distribution, indicating the distribution of luminance ratios within the rooms. The findings indicate the range and patterns of luminance values are between 15 to 300 cd/m2, whose highest luminance values are over 285 cd/m2. Purple signifies the areas with the least luminance, measuring 15 cd/m², while yellow indicates the brightest point, exceeding 500 cd/m². This completely contrast arises from the pronounced differentiation between the windows and the interior depths of the selected rooms. Hence, the purple colors represent the low luminance values (<15 cd/m2), and the red ones represent the high luminance values (>500 cd/m2). At 9 AM in the morning, the luminance at the windows attains approximately 1435 cd/m² in the East orientation, while it measures 274 and 350 cd/m² respectively. In the West orientation, the luminance reaches 414 and 353 cd/m². At noon, around 12 PM, the luminance values become uniform at 470 cd/m² for both the East and West orientations. As the day progresses to 4 PM in the evening, the luminance values reach about 414 and 466 cd/m² for the East room and 463 and 357 cd/m² for the West room.

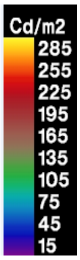
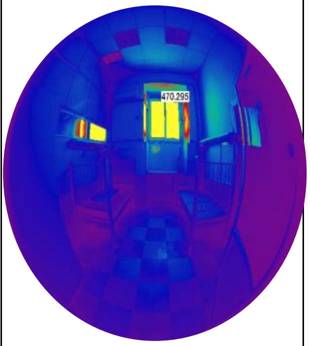
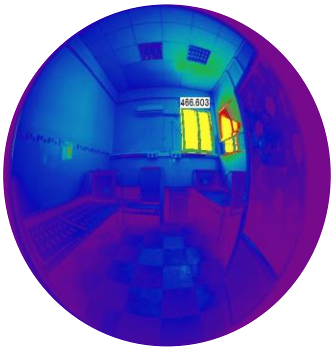
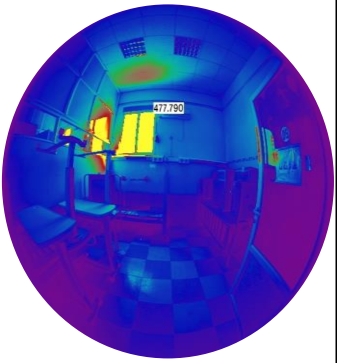
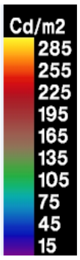
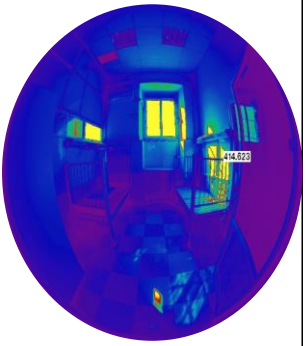
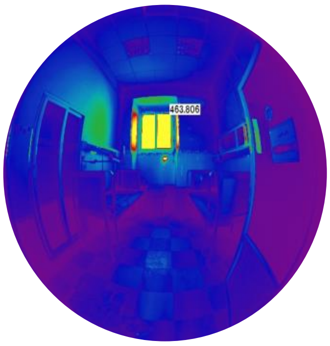
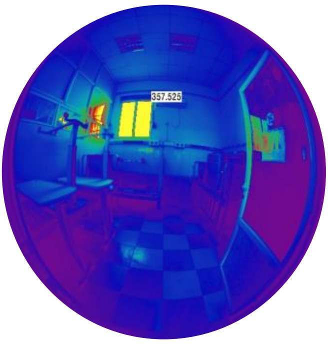
At summary, the false color analyses were similarly employed on the resultant images to showcase how the distribution of luminance ratios in the rooms is depicted through variations in color distribution. The outcomes reveal variations in luminance between different orientations. The results obtained from the measurements of luminance indicate that in the morning, the overall luminance exceeds the standard levels for the closest areas to the openings. However, during the afternoon, the illuminance drops below the recommended thresholds for the interior regions of the space. Notably, patient rooms oriented towards the south and west within the pediatric ward display exceedingly elevated illuminance levels. Such intensity of light can potentially have adverse effects on patient well-being, leading to discomfort due to overheating and glare.

The approach employed in this investigation has yielded numerous concrete outcomes that can assist researchers and architects in developing a robust understanding of the building environment and the characteristics of light. While HDRI and luminance measurement constitute its fundamental elements, the approach also capitalizes on other constituent parts. The entirety of these components needs to operate cohesively as an integrated system to comprehensively grasp the behavior of Daylight.

Table 4.4: HDR photos with Camera CANON and Fisheye False Color HDR images 180°

(Source: Author, 2022)

	East	East	West	West
9 AM				
12 AM				
4 PM				
9 AM  	 	 	 	

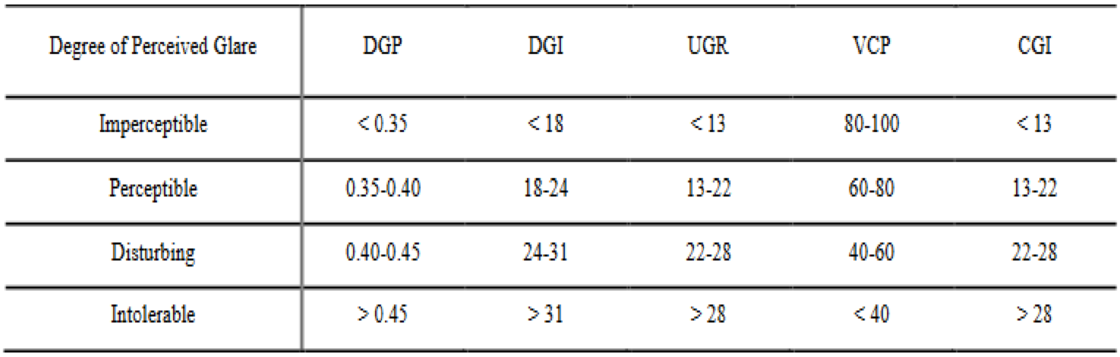
12 AM 				
4 PM 				

According to literature review, DGP is a recently developed glare metric specifically designed to assess daylight glare. It combines the vertical eye illumination as a measure of glare with the central component of established glare metrics, while also accounting for the influence of the glare source. In comparison to other existing glare metrics, DGP demonstrates a strong correlation with users' subjective perception of glare (Wienold and Christoffersen, 2005; Suk, J. Y. et al., 2016). DGI, on the other hand, was developed to evaluate glare from large sources such as high luminance windows (Bellia et al., 2008). While UGR, VCP, and CGI were initially created to address glare issues caused by artificial lighting sources, several studies suggest their potential applicability to daylight environments (Isoardi et al., 2012). Given these considerations, all five existing glare metrics were examined in this study. For automated assessment of glare in luminance, images captured using High Dynamic Range Imaging (HDRI), the software program Evalglare was developed (Wienold and Christoffersen, 2006). Evalglare identifies potential glare sources by applying a threshold value, which can be determined in three ways: 1) manually specified by the user as a fixed luminance value, 2) computationally determined based on the average luminance in the field of view, or 3) computationally determined based on a user-defined task location (Inanici, 2004 and 2005). Evalglare can be integrated into various daylighting analysis software programs, simplifying the process of glare analysis. However, its widespread adoption has been limited (Suk, J. Y. et al., 2016).

Evalglare integrated with Aftab-Alpha software calculates five glare metrics from HDR image, which can be in HDR or PIC format and either a 180-degree angular fisheye or a normal perspective. Toward inputting Evalglare commands in a DOS window or using hdrscope software, luminance values and locations of each pixel in the image are calculated. This information is then used to derive important values such as background mean luminance, glare source luminance, glare source position, solid angle of glare sources, vertical illuminance, and direct vertical illuminance. Based on this information, Evalglare provides glare scores and visual representations of potential glare source locations and sizes. The provided table illustrates the different ranges of glare scores for the five glare metrics, categorizing levels of perceived glare from imperceptible to intolerable. In DGP, DGI, UGR, and CGI, higher scores indicate more severe discomfort glare issues. However, in VCP, a higher score represents better visual comfort as it indicates the probability of comfort (Suk, J. Y. et al., 2016).

The human subject study data that was collected underwent analysis using the five established glare metrics (DGP, DGI, VCP, UGR, and CGI) (see Table 4.5). The glare scenes captured in HDR image format were appropriately edited in hdrscope before being processed in Evalglare to generate glare scores for each metric.

Table 4.5: Scale degrees of Glare in Different Glare Metrics (Source: Jakubiec, 2010; Suk, J. Y. et al., 2016)



Degree of Perceived Glare	DGP	DGI	UGR	VCP	CGI
Imperceptible	< 0.35	< 18	< 13	80-100	< 13
Perceptible	0.35-0.40	18-24	13-22	60-80	13-22
Disturbing	0.40-0.45	24-31	22-28	40-60	22-28
Intolerable	> 0.45	> 31	> 28	< 40	> 28

The aim of comparing the calculated glare scores with subjective evaluations was to assess the accuracy of each glare index in analyzing different daylight conditions. Given the inconsistent evaluation problem observed with the existing metrics in a previous study (Suk and Schiler, 2012), the expanded dataset was first evaluated to confirm the earlier findings and determine whether any inaccuracies would arise.

4.4. Conclusion

The chapter initiates with a succinct depiction of the geographical position and the prevailing healthcare structures within Biskra city. This segment serves to introduce the spectrum of health facilities in Biskra and opt for an appropriate hospital for the initial study. Following the hospital selection, measurements of daylight illumination were executed. The aim was to acquire comprehensive quantitative assessments of natural lighting within the patient rooms of the Pediatric ward at Hakim Sadaan Hospital. Additionally, the chapter delineates the methodology for measurements, data compilation, and the analysis of outcomes. Therefore, this empirical segment is geared towards recognizing issues and presenting optimal remedies to tackle them effectively.

The main objective of this chapter was to highlight the relationships that exist between the various variations in daylight, their impact on the experienced variations at each room. The first parameter measured is the illuminance level, and the second is the luminance values map and contrast level. It was focused on describing the fieldwork conducted in a specific study which is the assessment of daylight performance in patient rooms in Dr. Hakim Sadaane hospital that located in the city of Biskra. The objective of this chapter is to present and explain the protocol (procedures and steps) proposed in this research in order to collect all the necessary information in terms of quantitative data. The study, which focused on in situ measurements, was preceded by an overview of the climatic data of the study context, namely the city of Biskra. Subsequently, a typological analysis of the hospital and the patient rooms involved in the study was conducted. Before starting the measurement campaign, the selected rooms as case studies were presented for the purpose of evaluating natural lighting. Additionally, the measurement protocol was developed and described. To gather information on indoor illuminance, quantitative measurements were conducted in the models using a luxmeter Testo 480 Probe Lux (accuracy: ±5 % ±10d) and Camera CANON to measure Luminance levels. Alongside these measurements, spherical images were captured within various visual fields in both the reference and test models. Subsequently, the captured images were processed using the 'Aftab Alpha' software to derive 'D.GI.P' values. These values enable the analysis of the potential glare index present in the study models. Finally, the in situ evaluation of natural lighting performance in patient rooms was carried out. The two parameters tested were illuminance and luminance, and the measurements took place during the 2020-2021 academic year, covering both the hot and cold seasons.

The approach employed in this research has generated multiple concrete outcomes that can support researchers and architects in developing a comprehensive understanding of both the building environment and the behavior of light. While HDRI and luminance measurement serve as central elements, this method also leverages additional components. The integration and collaboration of all these components are essential for creating a cohesive system that enables a thorough comprehension of light behavior. Furthermore, this method has empirically validated several assumptions made by earlier researchers and has unveiled numerous facets concerning the penetration of natural light.

CHAPTER 5

BUILDING PERFORMANCE SIMULATION AND MODEL VALIDATION

5.1. Introduction

“.......*Lighting simulation is a hunt for light*...........”

John Mardaljevic

Daylight simulations involve utilizing computer calculations to evaluate the interior lighting conditions resulting from natural daylight. These calculations prove useful in the early stages of building design as they allow for quantitative comparisons of various design options. In a recent online survey conducted among 185 designers, engineers, and researchers from 27 countries, focusing on the "use of daylight simulation during building design," the findings revealed two key points. Firstly, an increasing number of design professionals now routinely employ daylight simulations to forecast daylight factor and interior illuminance distributions. Secondly, compared to previous surveys, there has been a notable increase in trust regarding the reliability of daylighting tools among practitioners (C.F. Reinhart, et al., 2006; Reinhart, C.F. & Andersen, 2006).

Daylighting plays a critical role in establishing indoor environments that are both comfortable and energy-efficient, while also enhancing the well-being and productivity of occupants. Towards conducting precise simulations and analyses of daylighting systems, architects, engineers, and researchers are able to make well-informed design choices and optimize the utilization of natural light within buildings. This field encompasses a range of factors, including predicting the availability, distribution, and quality of daylight within interior spaces. In addition, with utilizing advanced simulation tools and techniques like Grasshopper, Radiance, Daysim, Diva, and EnergyPlus, researchers can model and evaluate how various architectural features, materials, and shading systems impact aspects such as daylight penetration, illuminance levels, glare control, and energy consumption. Ensuring the reliability and accuracy of daylight simulation results involves a crucial step that called validation process, which entails comparing simulated data with real-case measurements gathered from physical prototypes or existing buildings. Through this process, researchers can assess the accuracy and performance of simulation tools, identify any discrepancies, and enhance the dependability of future simulations.

The simulation and validation performance study offer numerous advantages for building design and optimization. It empowers architects and designers to explore different daylighting strategies, evaluate their effects on indoor environments, and make informed decisions early in the design process. Moreover, it provides opportunities for energy optimization since daylighting simulations can assist in determining the most effective utilization of artificial lighting systems, thereby minimizing energy consumption. This area of research is continuously advancing, driven by progress in simulation tools, data collection techniques, and building performance evaluation. By deepening our understanding of how daylight interacts with architectural spaces, we can create built environments that are more sustainable, comfortable, and visually pleasing. The simulation and validation of daylight performance study play a pivotal role in achieving these objectives, contributing to the design of healthier and more energy-efficient buildings.

The initial part of this chapter provides an overview of the simulation procedure employed to acquire illuminance and daylight levels at the work plan. It begins with a brief description of the parametric design model and engines utilized in the simulation process, followed by an explanation of the methodology employed for conducting computer simulations. The subsequent section of the chapter outlines the design process for performance simulation step of the workflow. Lastly, the chapter delves into the validation section which is a fundamental step to know the precision of results, along with the corresponding simulation results.

5.2. Parametric simulation

In recent years, significant progress has been made in the field of numerical methods for assessing and optimizing buildings. These advancements have resulted in the development of a diverse range of software tools that enable the simulation and analysis of building performance, with a specific focus on thermal comfort, visual comfort, and energy efficiency. One notable software suite utilized in this study is the 'Honeybee & Ladybug' program, which functions as a collection of plug-ins integrated into the Grasshopper/Rhinoceros graphical platform. Grasshopper/Rhinoceros is widely recognized and extensively utilized as a graphical algorithm editor in the design, architecture, engineering, and construction domains. The 'Honeybee' plug-in facilitates the creation and manipulation of intricate 3D building models, while the 'Ladybug' plug-in offers comprehensive environmental analysis capabilities, encompassing tasks such as daylighting simulations, solar radiation analysis, and energy performance evaluations. When combined, these tools provide a powerful and versatile platform for conducting parametric design and performance analysis of buildings. With employing the 'Honeybee & Ladybug' plug-ins within the Grasshopper/Rhinoceros environment, seamless integration with other design and analysis tools is achieved, thereby streamlining the workflow for architects, designers, and engineers. This integrated approach empowers practitioners to explore various design alternatives, evaluate their performance, and optimize building parameters based on quantitative data. The popularity of the Grasshopper/Rhinoceros platform stems from its adaptability, visual programming interface, and extensive support from the professional community. Its widespread adoption by design, architecture, engineering, and construction professionals has established it as a widely respected and trusted tool for computational design and performance analysis. Towards leveraging the capabilities of the 'Honeybee & Ladybug' plug-ins within the Grasshopper/Rhinoceros environment, researchers and practitioners can conduct comprehensive evaluations of building performance, identify areas for enhancement, and make well-informed decisions to achieve improved thermal and visual comfort, energy efficiency, and overall sustainability in building design and construction.

5.2.1. Description of the parametric design model

A parametric approach was employed to the geometric model design using Rhinoceros and Grasshopper software of simulation as defined in (Chapter 2, section 3.2.5), along with integrated plugins like Ladybug and Honeybee. Several software programs, including Open-Studio, EnergyPlus, Radiance, Diva and Daysim, were utilized for daylighting and energy simulation.

Figure 5.1: (a) Base case modelling design and situation of studied patient rooms in perspective and top views in Rhino; (b) patient room model parameters in Rhino (Source: Author, 2021)

As depicted in Figure 5.1 illustrates the first case study block, representing the overall mass of the Pediatric Ward geometry within the hospital. For streamline the simulation process and overcome challenges, a single-zone room sample measuring 3.0 m × 3.0 m × 3.20 m (length × depth × height) was selected. The 3D model was developed in Rhinoceros, taking into account geometric measurements and the material characteristics of the selected patient rooms in the hospital Hakim Sadaane. The EnergyPlus materials for the existing base case were defined, and basic parameters were adjusted in Grasshopper. The exterior wall consists of alveolar bricks and single-glazed windows without shading devices which defined in Table 5.1 , 5.2 and Table 5.3 that summarize the physical and optical properties of the materials in the patient room, which serve as inputs for the building simulation process.

Table 5.1: Physic-optical properties of building materials used for the simulation model (Source: Author, 2021)

Rad material type (layers)	Reflectance/ Transmissivity*
White plaster	0.80
Interior plaster	0.80
Floor	0.40
Ceiling	0.80
Window wood	0.25
Glass material (Single glazing)*	0.90

Table 5.2: Building construction materials of the hospital Hakim Sadaan – External and Internal wall (Source: Hakim Sadaane hospital, DTR C 3-2 1997 Documentation Technique Réglementaire du Ministère du Logement, Algérie)

	Parameters	Unit	Exterior plaster coating	Brick25-alveolar	Interior plaster coating
External wall	T	m	0.01	0.50	0.01
	λ	W/(m·K)	1.1533	0.31083	0.35111
	D	kg/m3	1700	720	1500
	C	J/(kg·K)	1000	794	1000
	U-value	(W/m2-K)	5.597	0.491	5.038
Internal wall	T	m	0.01	0.18	0.01
	λ	W/(m·K)	1.35111	0.31083	0.35111
	D	kg/m3	1500	720	1500
	C	J/(kg·K)	1000	794	1000
	U-value	(W/m2-K)	5.038	1.335	5.038

Table 5.3: Building construction materials of the hospital Hakim Sadaan – floor and Roof (Source: Hakim Sadaane hospital, DTR C 3-2 1997 Documentation Technique Réglementaire du Ministère du Logement, Algérie)

Parameter	Unit	Floor Materials			Roof Materials				
		Flooring	Floating slab	CALC1_T_N2	Sealing	Compression Slab	Steel	Air cavity	Interior Plaster coating
T	m	0.20	0.10	0.30	0.1	0.05	0.03	0.30	0.02
λ	W/(m·K)	1.714	1.755	1.230	1.75	1.755	44.4	$6.027e^{-2}$	0.351
D	kg/m3	2300	2300	1500	2300	2300	7800	1	1500
C	J/(kg·K)	700	920	800	920	920	510	1227	1000
U-value	(W/m2-K)	3.480	4.406	2.062	4.40	5.038	5.85	0.194	4.406

5.2.2. Design process for the performance simulation

The previous section introduced two simulation engines that were employed for conducting annual dynamic simulations. Initially, Radiance integrated plugin in Grasshopper + Rhinoceros 6.0 software was utilized to accurately simulate illuminance levels on the work-plane and Daylight factor. Subsequently, EnergyPlus was employed to estimate the total annual energy demand for lighting, heating, and cooling. Since these two simulation engines are not inherently compatible, a programming language (Python) was utilized to establish a connection between them.

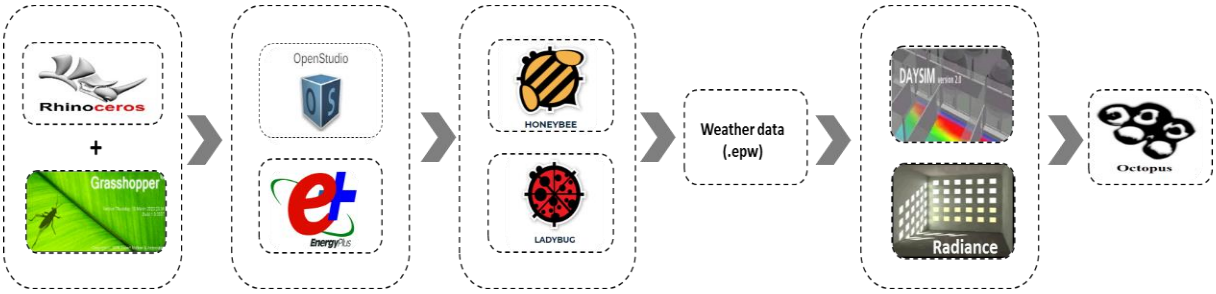


Figure 5.2: Algorithmic design process of software and plug-ins coupled in the workflow (Source: Author, 2021)

The optimization objectives in this study were to minimize Energy Use Intensity (EUI) and achieve maximum of spatial daylight autonomy (sDA), and Useful Daylight luminance (UDI). Figure 5.2 describes the algorithmic design process of software and plug-ins coupled in the workflow; it is developed in Rhino/ Grasshopper with the integration of plugins for fulfilling the objectives of this study: Rhino is used as a modelling tool and Grasshopper as a parametric design tool for daylight analysis and energy performance application. Further, Honeybee 0.0.69 and Ladybug 0.0.69 is utilized as a main environmental plug-in for obtaining the energy and daylight simulation feedback. Moreover, the optimization was carried out using a multi-objective tool to find the best design schemes, which is Octopus plugin.

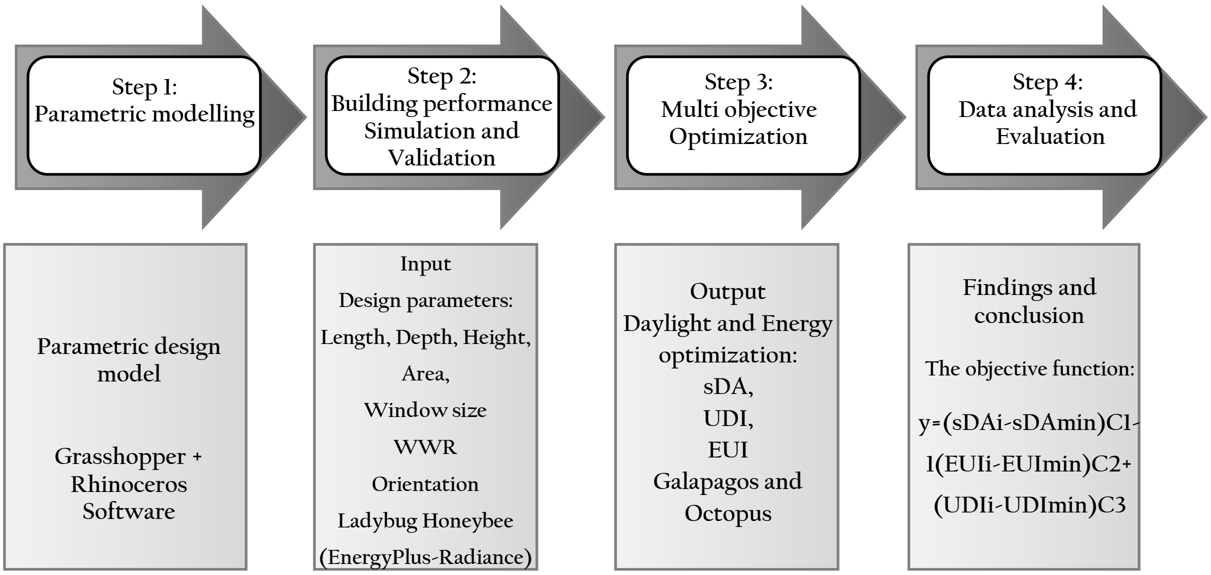


Figure 5.3: Research design diagram proposed for the simulation and optimization process (Source: Author, 2021)

In Fig.5.3, The workflow described above which illustrates the overall framework of research design diagram proposed for the simulation and optimization process. The process consists of four primary steps. Firstly, the initial step involves identifying design parameters and constructing a parametric design model. In the second step, daylight and energy simulations are developed, which includes a crucial validation section to assess the accuracy of the results. The corresponding simulation outcomes are also obtained during this phase. The third step focuses on the optimization process, which includes optimizing daylighting, energy, and multi-objective aspects considering both daylighting and energy. Various optimization techniques are applied to enhance the design based on these factors. Lastly, moving on to the fourth step, it involves the analysis and evaluation of simulation data and the optimized design following the optimization processes. Visual comparisons are made between the optimal designs, and the settings of each optimized design are thoroughly examined. Furthermore, the improvement in building performance is assessed, and the variables that exert the most significant influence on the building performance are analyzed.

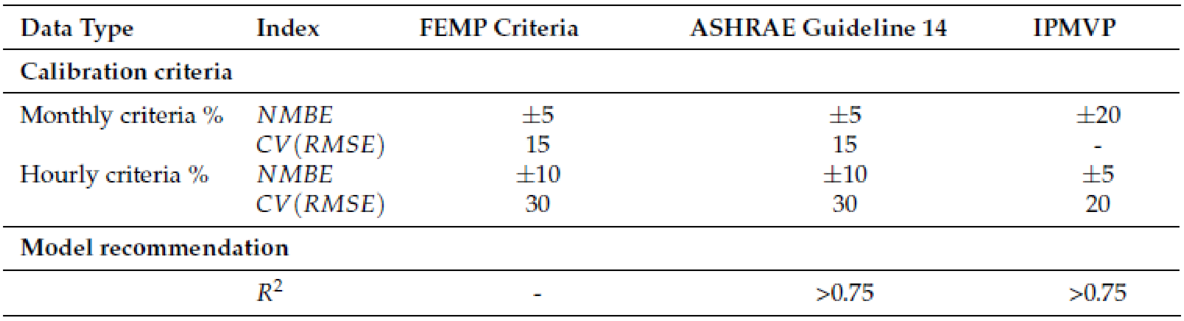
5.3. Model validation

5.3.1. Definition of the validation step

The validation phase is an essential component in assessing the accuracy and reliability of simulation results, particularly when it comes to daylighting performance simulation, which presents challenges in achieving precise predictions (Andrew L. Hook et al., 2023).Validation analysis is a crucial procedure that involves comparing and confirming the precision and dependability of simulation outcomes by cross-referencing them with real-world measurements or established reference data. It plays a vital role in evaluating the faithfulness and effectiveness of simulation models and tools. During validation analysis, simulated data is juxtaposed with experimental data or measurements acquired from physical prototypes or existing buildings. The main objective is to ascertain the level of concurrence between the simulated and real-world results. Through the execution of validation analysis, researchers can evaluate the accuracy of the simulation models and identify any discrepancies or areas that require improvement. Validation analysis commonly employs statistical methods to quantify the level of agreement, employing techniques such as mean absolute error, root mean square error, or correlation coefficients. These statistical measures offer valuable insights into the precision and reliability of the simulation results. The validation process serves to ensure that simulation models are adequately calibrated and validated against empirical data, enhancing their predictive capabilities. It instills confidence in researchers and practitioners, enabling them to make well-informed decisions based on validated models (Andrew L. Hook et al., 2023).

Model validation aims to assess the accuracy and predictive capability of the model by comparing its predictions with an unknown dataset from the real world (Cheng and Sun, 2015). This evaluation involves calculating various quality parameters, collectively known as figures of merit, which include accuracy, linearity, adjustment, sensitivity, analytical sensitivity, limits of detection, and quantification. Accuracy is represented by the root mean square error of calibration (RMSEC) and prediction (RMSEP). Additionally, RMSECV is considered, as an ideal multivariate calibration model demonstrates similar values for RMSEP, RMSEC, and RMSECV, indicating that random errors are effectively captured within the model (Evandro Bona et al., 2018). The primary uncertainty indices employed include the Normalized Mean Bias Error (NMBE), Coefficient of Variation of the Root Mean Square Error (CV(RMSE)), and coefficient of determination (R2). However, it is important to begin by defining the Mean Bias Error (MBE) as it holds significance when explaining the analysis and magnitude of the error. The Mean Bias Error (MBE) represents the average of errors within a given sample space, as implied by its name. It serves as an effective indicator of the overall behavior of the simulated data in relation to the regression line of the sample, providing valuable insights into its performance (Cook, D.A. & Hatala, R., 2016). NMBE (Normalized Mean Bias Error) is a normalized version of the MBE index, which allows for a standardized comparison of MBE results. It measures the magnitude of the MBE index by dividing it by the mean of the measured values (m^{-}), thereby providing an assessment of the overall disparity between the actual values and the predicted values (Ramos Ruiz, G., & Fernandez Bandera, C., 2017). According to the Table 5.4, this table summarizes the criteria outlined in the three main documents for validating a calibrated model (Webster, L. & Bradford, J., 2008; Webster, L. et al., 2015; ASHRAE). Guideline 14-2014; (ASHRAE). Guideline 14-2002).

Table 5.4: The calibration criteria set forth by the Federal Energy Management Program (Source: Ramos Ruiz, G., & Fernandez Bandera, C., 2017)



Data Type	Index	FEMP Criteria	ASHRAE Guideline 14	IPMVP
Calibration criteria				
Monthly criteria %	$NMBE$	±5	±5	±20
	$CV(RMSE)$	15	15	-
Hourly criteria %	$NMBE$	±10	±10	±5
	$CV(RMSE)$	30	30	20
Model recommendation				
	R^2	-	>0.75	>0.75

5.3.2. Daylight validation literature review

Every daylighting calculation is subject to uncertainty, which is inherent and inevitable. This uncertainty exists alongside any potential errors resulting from inaccuracies in a numerical model. It arises from the inability to predict the future state of a building or the luminance pattern of the sky with absolute certainty. Furthermore, the theory of daylight coefficients is expanded upon. It is demonstrated that the daylight factor under a uniform sky is equivalent to twice the mean of the daylight coefficients. This equivalence allows for the comparison of criteria used in climate-based simulation with older daylighting standards (Tregenza, P. R., 2017). When it comes to validating daylight simulations, the lack of a standardized procedure and the presence of multiple documents make it challenging to ascertain the accuracy of errors. Researchers have not yet established a specific standard in this regard. Nevertheless, it is essential to consult the recommendations provided by recent studies that are globally recognized and follow a consistent approach to validation work (Nocera, F., 2018). For instance, according to Mardaljevic (1995 - 2000) conducted a series of three papers (Mardaljevic, J., 1995; Mardaljevic, J., 2000) that compared measurements of interior illuminances with Radiance simulations. These simulations were based on sky scanner data collected simultaneously with the measurements. The data set used in the study was collected by Aizlewood (1993) at the Building Research Establishment (BRE). The purpose of selecting this specific data set was to isolate and determine the simulation errors solely caused by the Radiance lighting algorithm, without any additional errors resulting from the representation of the sky (Mardaljevic, J., 2000; Reinhart, C.F.; Andersen, M., 2006). In 2000, Mardaljevic presented a third Radiance validation study, using the same data as in 1997. In this study, Radiance was combined with a daylight coefficient approach to more effectively simulate indoor illuminance (P.R. Tregenza et al., 1983). The results indicated that the daylight coefficient-based Radiance simulations can be considered nearly equivalent in accuracy to the standard time-step-by-time-step calculation (Mardaljevic, J., 2000; Reinhart, C.F.; Andersen, M., 2006). Another study conducted by Mardaljevic J. (2004), This research investigates the common assumptions made during validation studies of lighting simulation programs and evaluates how uncertainties in key model parameters, such as sky conditions and surface reflectivity, can affect the accuracy of the results. The research demonstrates that relying on commonly made assumptions about sky conditions and moderate imprecision in model parameters can lead to inaccurate assessments of program accuracy. The study also discusses the limitations of extrapolating existing validation findings to different application scenarios, considering conflicting assessments of program accuracy reported in the literature. To address these issues, the study proposes a methodology to minimize the influence of confounding factors that can introduce imprecise estimates of surface reflectivity for building facades. Additionally, the paper tests the validity of the assumption that real overcast skies closely resemble the CIE standard overcast sky for the purpose of comparing predictions against measurements in real buildings, using measurements of the sky luminance distribution for real skies (Mardaljevic J., 2004). In a study conducted by Andersen et al. (2021), the researchers concentrated on validating dynamic daylighting simulations. They compared the levels of measured and simulated daylight in an actual office building and observed that the simulations tended to overestimate the daylight levels. The study identified inaccuracies in model assumptions and input parameters as factors contributing to these discrepancies. Chen and Wang (2020) undertook a validation study that focused on various daylight metrics used in building performance simulations. They compared the simulated daylighting performance with field measurements in a school building. The results highlighted variations in the accuracy of different metrics, emphasizing the importance of carefully selecting appropriate metrics to achieve accurate daylight predictions. Brembilla, & J. Mardaljevic (2019) conducted a study to investigate the validation of climate-based daylight modeling techniques. They compared simulation results with measured data from a case study building and found good agreement for most of the tested metrics. However, discrepancies were identified in specific scenarios, indicating the need for further improvements in modeling techniques. In a recent study by Taveres-Cachat, E., & Goia, F. (2020), this research paper presents a study aimed at validating a modeling approach incorporated in a numerical script for external louvred shading systems. The validation process involved an experimental analysis conducted in a full-scale test facility. The developed model, which encompassed the shading system, was entirely parametric and employed co-simulation techniques to predict indoor air temperature and illuminance levels at two specific points within the test cell. To calibrate the model, a combination of two methods was employed: automated calibration using multi-objective optimization with a genetic algorithm and manual calibration. The performance of the model was evaluated using three metrics: root mean square error, coefficient of variation of the root mean square error, and normalized mean bias error. The results demonstrated that the daylighting model adequately captured the diverse dynamics of illuminance peaks and dips, effectively reproducing variations between different configurations. However, it exhibited a lower level of accuracy compared to the thermal simulations (Taveres-Cachat, E., & Goia, F., 2020). Pellegrino, A., et al. (2018) conducted a comparative study that examines the accuracy of a simplified approach, proposed in the European standard EN 15193, for calculating daylight supply in buildings. The simplified method was compared with dynamic simulations conducted using the DIVA-for-Rhino software. The study specifically focuses on two parameters: the daylight factor (D) and the daylight supply factor (FD,S). The findings reveal a strong correlation between the simplified method and dynamic simulations when calculating the daylight factor. However, there was a lower correlation observed when calculating the annual daylight contribution, primarily due to the complexity of the variables involved. The study offers valuable insights for optimizing and implementing the EN 15193 standard, particularly regarding the influence of climate conditions and the usage of movable shading devices. The standard itself, EN 15193-1 (2017), was developed to support the Energy Performance of Buildings Directives and includes a metric for quantifying the energy demand for lighting in buildings (Pellegrino, A., et al., 2018; Osborne, J., 2013; Farzam Kharvari, 2020; Mousavi, S., M. et al., 2016).

These studies collectively demonstrate the ongoing efforts to validate daylighting simulations and enhance their accuracy. They underscore the significance of carefully considering model assumptions, input parameters, and the specific context of the simulated building. The findings contribute to the continuous advancement of reliability and effectiveness in daylight simulation tools for architectural and building design practices.

5.3.3. Daylight validation of the digital model

Based on the literature review conducted in the preceding section, it is imperative to consult the recommendations put forth by recent globally recognized studies that adhere to a similar approach in validation-related research. These studies serve as essential references for ensuring the accuracy and reliability of validation methodologies and techniques. Toward referring to these recent studies, researchers and practitioners can stay updated with the latest advancements in the field and gain insights into best practices for conducting validation analyses. The findings and recommendations of these studies contribute to the ongoing development and improvement of validation frameworks, enhancing the overall quality and credibility of research outcomes. The chart depicted in Figure 5.4 (see Appendix D), illustrates the contrast between measured illuminance values and simulated values at the work plane. In order to facilitate a comparison between the measured data and the simulation results, it is crucial to initiate the evaluation process by calculating the relative error (RE). The relative error serves as a metric for assessing the accuracy of the errors and is computed as follows (see Equation 5.1):

$$\boldsymbol{RE = \frac{(Mi - Si)}{Mi} * 100\%} \qquad (1)$$

As indicated in Table 5.5, the measured illuminance value (MI) and the corresponding simulated illuminance value (SI) at each measurement point were recorded (Nocera, F. et al., 2018; Costanzo, V. et al., 2022). In energy and thermal validation, it is typically expected to have a percentage of errors below 5% (Reinhart, C.F., & Andersen, M., 2006). However, in the case of daylight validation, previous studies have considered relative errors in the range of 20-30% to be acceptable (Ruiz, G.; Bandera, C., 2017). In this study, the relative error values for most of the measured and simulated illuminance values were below 20%, which falls within the acceptable range according to recommendations from recent studies.

Table 5.5: Measured and simulated illuminances calibration; Relative Error RE in December at 9:00 h; 12:00 h and 16:00 h (Source: Author, 2021)

Time	Room	Measured average illuminance	Simulated average illuminance	Relative Error (RE)
9:00h	Room 1	475.33	493.77	-3.89
	Room 2	314.33	277.88	11.59
	Room 3	428.22	477.44	-11.49
12:00h	Room 1	730	820.22	-12.36
	Room 2	536.33	546.55	-1.91
	Room 3	505,44	651.22	-28.84
16:00h	Room 1	143.22	152.33	-6.36
	Room 2	134.44	135.66	-0.91
	Room 3	132.66	128.33	3.26

To further evaluate the comparison between the measured and simulated results, additional error calculations were performed using the mean bias error (MBE) (see Equation 5.2) and the coefficient of variation root mean squared error (CV (RMSE)) (see Equation 5.3), as outlined in the ASHRAE 14-2014 guideline (Reinhart, C.F. & Breton, P.F., 2009; McNeil, A. & Lee, E.S., 2013). These statistical indices were employed in this study to assess the similarity or difference between the measured and simulated illuminance data (Ruiz, G.; Bandera, C., 2017).

$$\boldsymbol{MBE} = \frac{\sum_{i=1}^{n}(\boldsymbol{Mi} - \boldsymbol{Si})}{\sum_{i=1}^{n}\boldsymbol{Mi}} * \mathbf{100\%} \qquad (2)$$

$$\boldsymbol{CV(RMSE)} = \frac{1}{\bar{Y}}\sqrt{\frac{\sum_{i=1}^{n}(\boldsymbol{Mi} - \boldsymbol{Si})^2}{\boldsymbol{n}}} * \mathbf{100\%} \qquad (3)$$

Where: Mi is the measured value and Si is the simulated value at time interval I. n: is the total number of values used for the calculation. ȳ is the mean value of measured data.

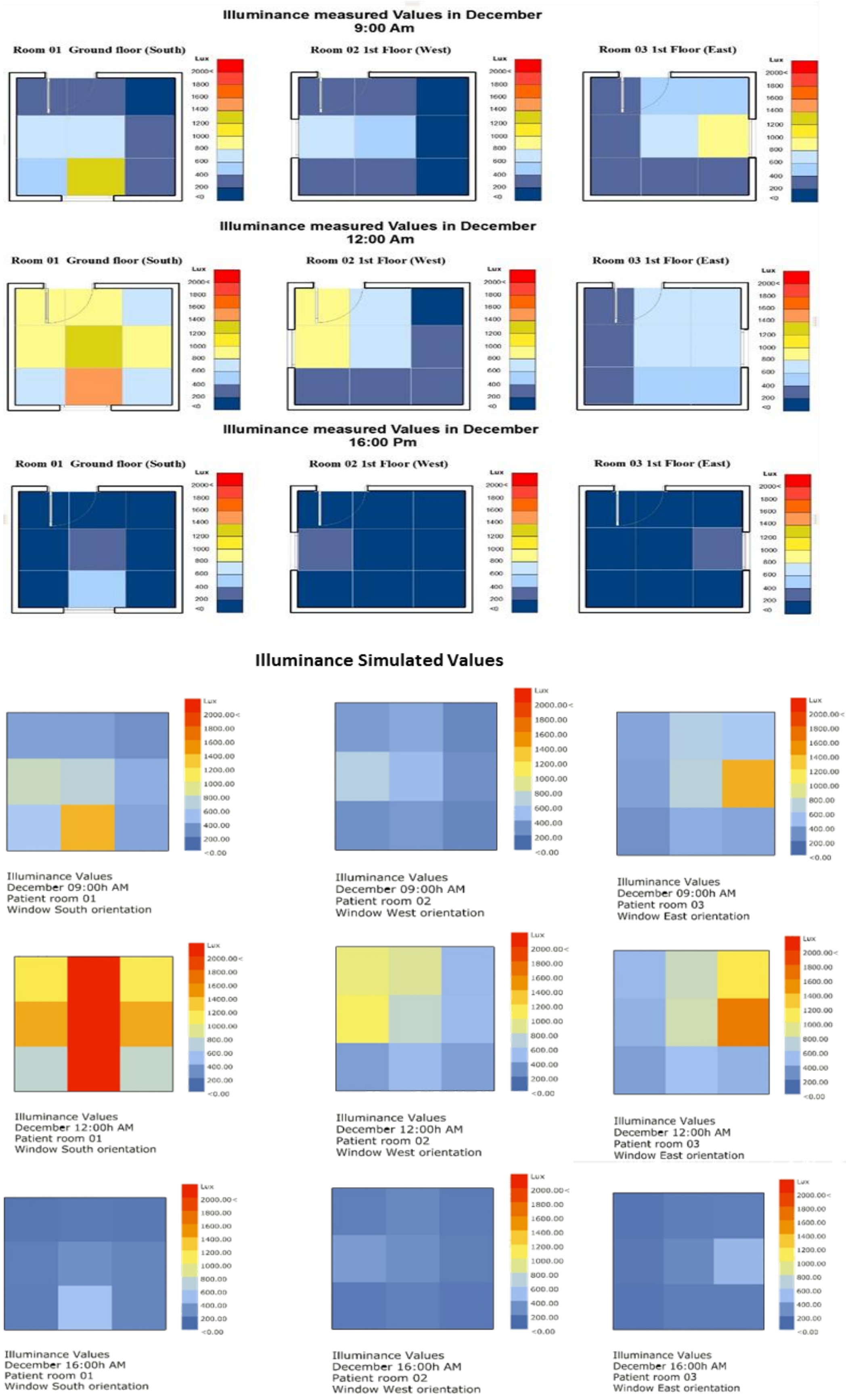


Figure 5.4: Comparison of measured and simulated illuminance levels in the patient room cases (Source: Author, 2021)

According to Reinhart and Breton (2009), the accuracy is achieved when the mean bias error (MBE) is below 15% and the root mean squared error (RMSE) is below 35%. A study by A. McNeil and E.S. Lee (2012) reported even lower values with MBE below 13% and RMSE below 23%. In the study conducted by Reinhart and Anderson (2006), MBE ranged from 8% to 17% and RMSE ranged from 24% to 40%. Another study by Reinhart and Walkenhorst (2001) found MBE to be 20% and the coefficient of variation root mean squared error (CV (RMSE)) to be 32%. In this study, the MBE and CV (RMSE) values were determined as shown in the Figure 5.5; in the first patient room, the MBE was -34.90% and the CV (RMSE) was 17.84%; in the second patient room, the MBE was -15.18% and the CV (RMSE) was 21.08%; and in the third patient room, the MBE was -25.48% and the CV (RMSE) was 20.81%. These values fall within the range of previous studies. These results demonstrate that the simulation method accurately generated a realistic model and can be considered valid (Tregenza, P.R., 2016).

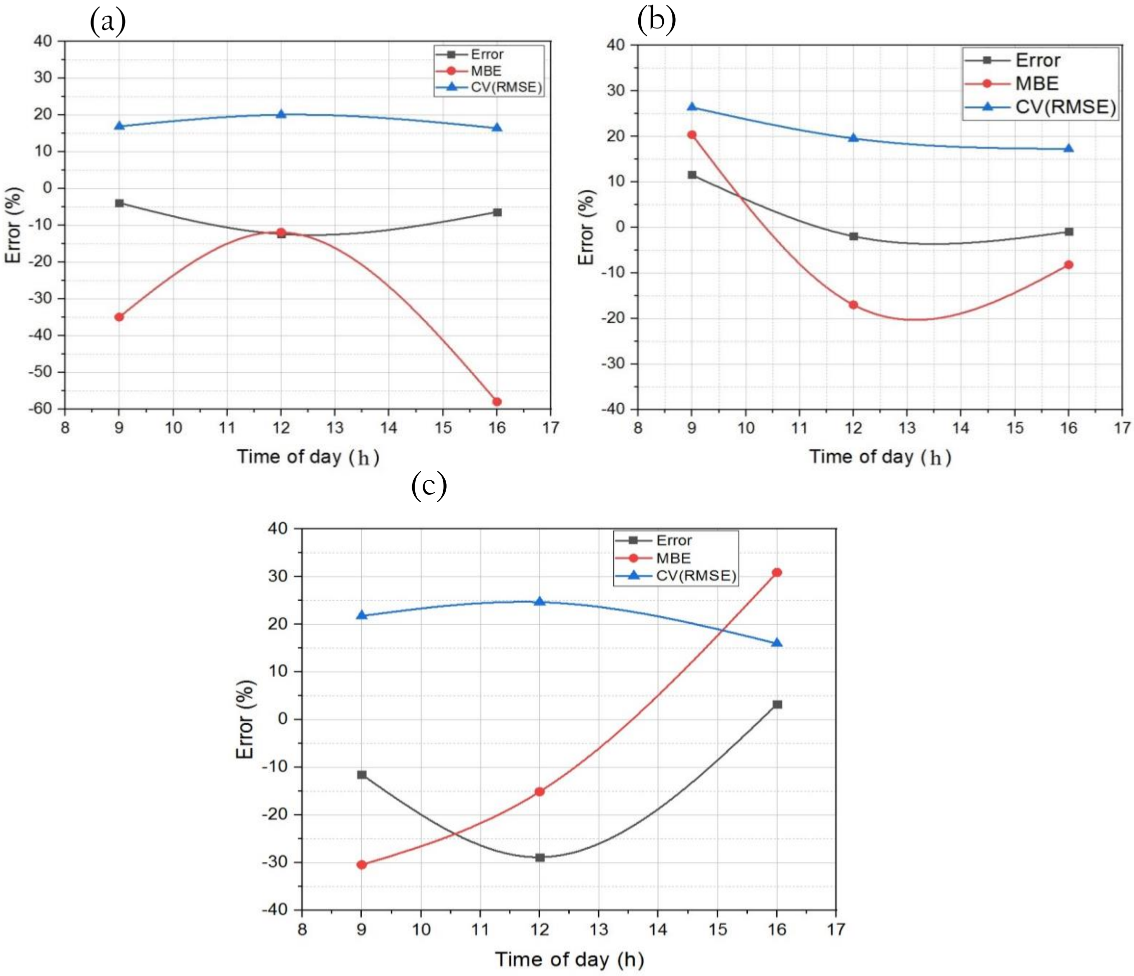


Figure 5.5: Distribution of the Relative error (RE), MBE and CV (RMSE) for the three patient room cases (a) Room 1; (b) Room 2; (c) Room 3 (Source: Author, 2021)

Furthermore, without further calibration, the validation step during the December period yielded acceptable results for this model. This allows for the implementation of optimized indoor daylight performance strategies in terms of illuminance, achieving the recommended values.

5.3.4. Luminance validation

Luminance validation is a crucial procedure employed to evaluate and authenticate the precision of luminance measurements in lighting systems or environments. Luminance refers to the quantity of light emitted, reflected, or transmitted by a surface in a specific direction, and it significantly influences the perceived brightness and visual comfort in both indoor and outdoor spaces. During the process of luminance validation, the measured luminance values are compared to well-established standards or reference values to ensure that the lighting system operates as intended. This evaluation helps in identifying any inconsistencies or errors in the measurements, enabling necessary adjustments or corrections, if required. Several methods and instruments are available for luminance validation, depending on the specific application and requirements. These include luminance meters, photometers, or spectroradiometers, all capable of accurately gauging luminance levels under varying lighting conditions (Kong, Z. et al., 2018; Nyboer, A. et al., 2021).

The validation process entails taking measurements at specific points or areas of interest within the lighting environment. These measurements are subsequently compared to recommended or desired luminance levels appropriate for the particular application. For instance, in architectural lighting design, luminance validation may involve assessing the uniformity and consistency of light levels across a space to ensure optimal visual comfort and aesthetically pleasing illumination. Luminance validation holds paramount importance for several reasons. Firstly, it ensures compliance with lighting standards and regulations, which often stipulate minimum and maximum luminance levels for diverse environments. This aspect is especially critical in areas where visual tasks or activities are performed, such as offices, educational institutions, or healthcare facilities. Secondly, luminance validation facilitates the detection of potential issues or deficiencies within the lighting system. These may encompass variations in light output, uneven distribution of light, or glare, all of which can adversely impact visual comfort and performance. Detecting such issues at an early stage enables appropriate adjustments to be made, optimizing the lighting design and enhancing the overall quality of illumination. Thirdly, luminance validation furnishes valuable data for research and analysis purposes. It empowers researchers and lighting professionals to evaluate the efficacy of different lighting strategies, assess the influence of lighting on human perception and behavior, and formulate guidelines for enhanced lighting design practices. Moreover, luminance validation assumes a critical role in evaluating and verifying the accuracy and performance of lighting systems. By comparing measured luminance values against well-established standards and reference values, this process ensures adherence to lighting regulations, identifies potential issues, and offers valuable insights for lighting design and research endeavors (Kong, Z. et al., 2018; Nyboer, A. et al., 2021; Kim, M., & Tzempelikos, A., 2021).

High dynamic range imaging (HDRI) is a photographic technique utilized for measuring lighting metrics and is commonly employed to analyze visual environments by creating luminance maps. However, there is a lack of research exploring the use of HDRI for evaluating illuminance (Suk, J. Y. et al., 2016; Saadi, M. Y., 2019). This project aims to investigate the feasibility of using HDRI to obtain illuminance values in an outdoor setting. While previous studies have demonstrated the accuracy of HDRI as a luminance mapping tool with an error rate of 10%, no research has explored its potential as an illuminance data acquisition tool specifically for exterior scenes. The objective of this research is to validate the use of HDR photography in generating illuminance maps for the evaluation of large outdoor environments. Additionally, the study addresses crucial aspects of HDRI data collection, including error reduction techniques, common mistakes to avoid, and specific considerations that require attention. Field measurements and measurements derived from HDR images were carefully evaluated and compared. The findings of this research indicate that the proposed methodology can be effectively employed to accurately estimate illuminance values obtained through HDRI in exterior environments (Kong, Z. et al., 2018; Nyboer, A. et al., 2021; Kim, M., & Tzempelikos, A., 2021). Obtaining illuminance data from HDRI is relatively less common compared to the extraction of luminance data. Various applications have been identified for utilizing HDRI in illuminance measurement and analysis. These include measuring illuminance on specific task areas as demonstrated by Bellia et al. (2011), mapping the distribution of luminous intensity of a light source using the illuminance map through the application of the photometric inverse law as explored by Bellia and Spada (2013), validating a technique for measuring complex illuminance values across large areas as studied by Mardaljevic et al. (2009), and measuring the illuminance contributions of architectural features as examined by Moeck and Anaokar (2006). These studies showcase the diverse potential applications of HDRI in illuminance measurement and highlight its relevance in different contexts within the field (Zhe Kong, D., 2018; Pierson, C., 2019 ; Saadi, M. Y., 2019; Kong, Z. et al., 2018 ; Au, P. P. Y., 2013).

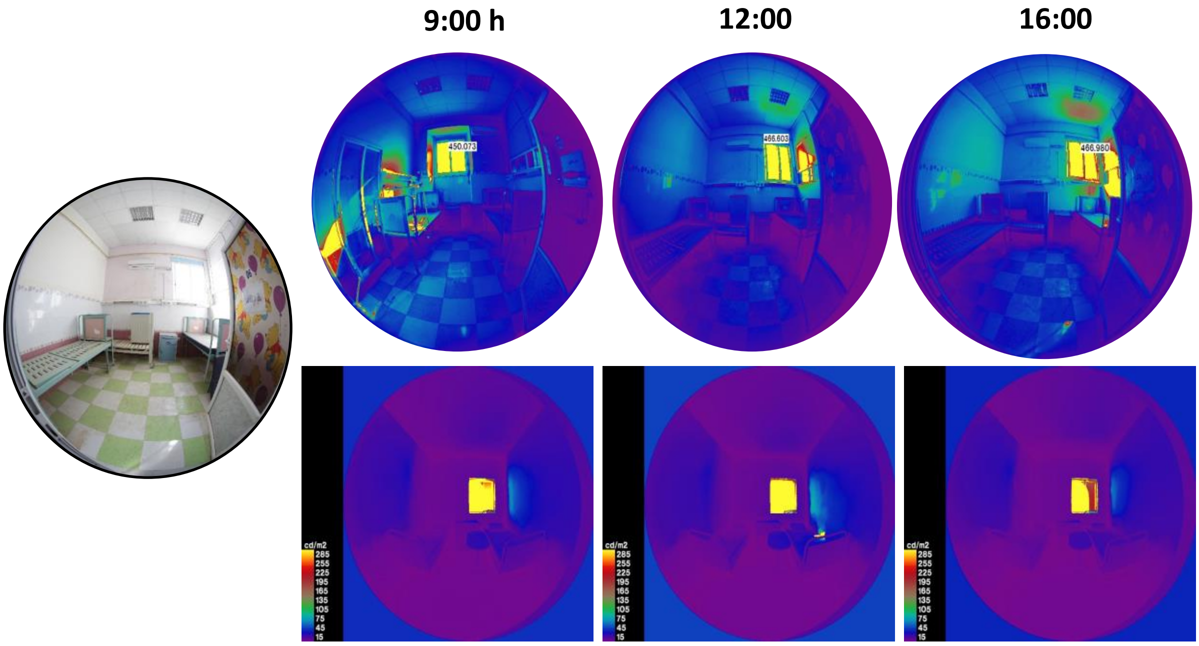


Figure 5.6: A comparison was made between the luminance values obtained from HDR images and the simulated luminance maps (Source: Author, 2021)

As seen in Figure 5.6, illustrates the comparison between the real falsecolor of HDR images and simulated luminance images for the East oriented patient room is displayed to calibrate the model for simulation. The falsecolor images in the three times over the day (9 Am, 12 Am and 4 Pm) demonstrate most similar distributions of luminance between the HDR images and the simulated luminance maps. The images generated through Radiance simulation were free from fisheye lens distortion, leading to challenges in directly comparing individual pixels between the actual and simulated data due to misalignment of geometric shapes. The both Images maps illustrate the span and configurations of luminance values, ranging from 15 to 300 cd/m^2 in the same scale, with the peak luminance values surpassing 285 cd/m^2. The color purple designates zones with minimal luminance, measuring 15 cd/m^2, whereas yellow denotes the most brilliant point, exceeding 500 cd/m^2. This sharp divergence originates from the noticeable contrast between the windows and the interior recesses of the chosen rooms. Consequently, the purple hues symbolize low luminance values (<15 cd/m^2), and the red hues signify elevated luminance values ranging from 400-455cd/m^2.As shown in the pair of images below, the correlation between the image comparisons is approximately 70%. Nonetheless, a considerable portion of the area exhibits a disparity exceeding 30 cd/m^2 due to misalignment of materials in the software. When comparing the simulated luminance maps to the valid HDR images captured on-site, it is observed that the simulated maps accurately predict glare in 52% of cases. This finding aligns with the conclusions drawn by Jones and Reinhart. The method of comparison employed involved utilizing a visual field map image. This image facilitated the comparison of illuminance values recorded during the monitored day with the simulated images produced through the use of the Grasshopper software with Radiance (Visual Field Comparison). Ensuring uniformity in picture resolution, scale, and image size between the two images was of utmost importance during the comparison process (see Figure 5.6). Despite of the geometric disparity between the actual and simulated images, the pixel-to-pixel comparison emerged as the least precise technique among the four employed. The incongruity in geometric shapes renders the comparison between the two images exceptionally challenging and imprecise. Both images underwent conversion into false color renderings within Radiance, utilizing identical luminance scales.

5.4. Results of base case building simulation assessment

5.4.1. Daylight performance results

In terms of Daylight Factor (DF) analysis, the results indicate that the majority of the Daylight Factor values in the patient room facing south and West orientation are above the recommended minimum level of 1% (Alzoubi, H. & Al-Rqaibat, S., 2015; Konis, K. et al., 2016). However, in areas directly in front of the window (as shown in Figure 5.7), the absence of shading devices can lead to visual discomfort and excessive daylight and solar irradiation. To address this issue, a shading device system can be implemented to control the daylight and keep it below 1% (Andersen, P.A. et al., 2014; Besbas, S. et al., 2022).

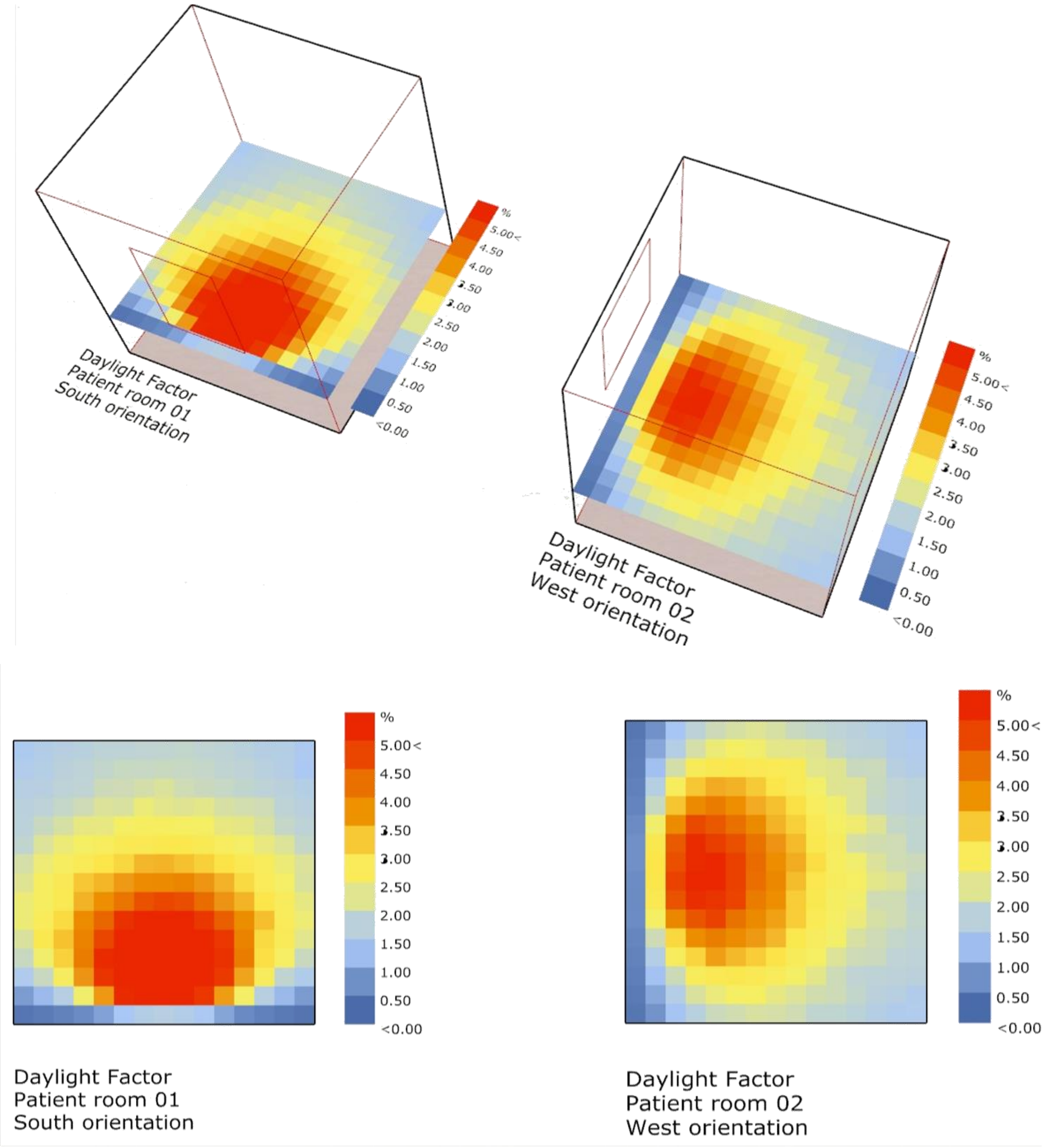


Figure 5.7: Daylight simulation of the base case patient room South and West orientations (Source: Author, 2021)

Once the simulation model was validated and the optimization objectives (sDA, UDI, EUI) were determined, a base case analysis was conducted. The results reveal that the average value of sDA, which represents the percentage of occupied hours when the indoor environment receives at least 300 lux of daylight, is 44.3% as see Table 5.6 (Pellegrino, A. et al., 2017; Tabadkani, A. et al., 2018).

Table 5.6: Characteristics of the original design case (Source: Author, 2021)

optimization objectives	Y	sDA %	UDI %	EUI (KWH/ m2)	Wall construction	Glass material	Shading Width Variations	Shading Count	Shading Angle
Original Design base case	_	44.3	35.2	158.1	Brick wall with air cavity	Single clear glass	_	_	_

This value is lower than the recommended threshold of approximately 75% of the total room area, as suggested by Ahmed Sherif et al. (2016). The sDA calculation takes into account the window resource, which allows a significant amount of direct and reflected sunlight to penetrate the room. In terms of the Useful Daylight Illuminance (UDI) metric, which determines the percentage of annual hours when daylight illuminance falls within an acceptable range at a specific point, as well as the total number of occupied hours (Nabil, A. & Mardaljevic, J., 2005; Mardaljevic, J., 2015), the recommended range for patient rooms is between 100 and 300 lux. In this case, the average UDI is 35.2% (Mardaljevic, J., 2012). The distribution of UDI levels is uneven, with 70% of the room surface experiencing UDI below 30%, while areas closer to the windows reach UDI levels exceeding 100% (Besbas, S. et al., 2022).

Lastly, with respect to the Energy Use Intensity (EUI) metric, the results indicate an annual average consumption of 158.1 KWh/m2/year for heating and cooling in the base case model. Compared to the other metrics, the energy simulation yields reasonable results due to the moderate ratio of window-to-wall ratio (WWR) on the southern elevation. A lower EUI value signifies better energy efficiency. Consequently, the next step in optimizing the model will be to further reduce the EUI values.

5.4.2. Illuminance results

The process of simulating illuminance metrics involved employing Grasshopper and Rhinoceros. Grasshopper's extensions, utilizing Radiance and Daysim simulations, were utilized. These extensions facilitated the assessment of daylight performance and building availability. In the scenario involving a grid setup, 150 individual grids were deployed per model. An illustration of the fundamental model can be observed in Figure 5.8, depicting rooms with south and west orientations. Displayed is a three-dimensional representation of the daylight simulation model. The outcome of each output attribute was derived from the annual average value of every analysis surface, as showcased in Figure 5.9. Consequently, the assessment visuals depict areas shaded in a spectrum from red to yellow, indicating elevated illuminance levels within the interior of the room design prototype. The measurements reveal values well exceeding 700 lux (approximately reaching +2000 lux) in close proximity to all openings, offering more than threefold the illumination required for visual tasks within the room, as illustrated in Figure 5.8. During the month of December, the mean illuminance level reaches around 700 lux for rooms facing the West, but surpasses 2000 lux for those oriented to the South. This discrepancy highlights an inequity in lighting distribution concerning temporal aspects, orientation, and depth within each patient room.

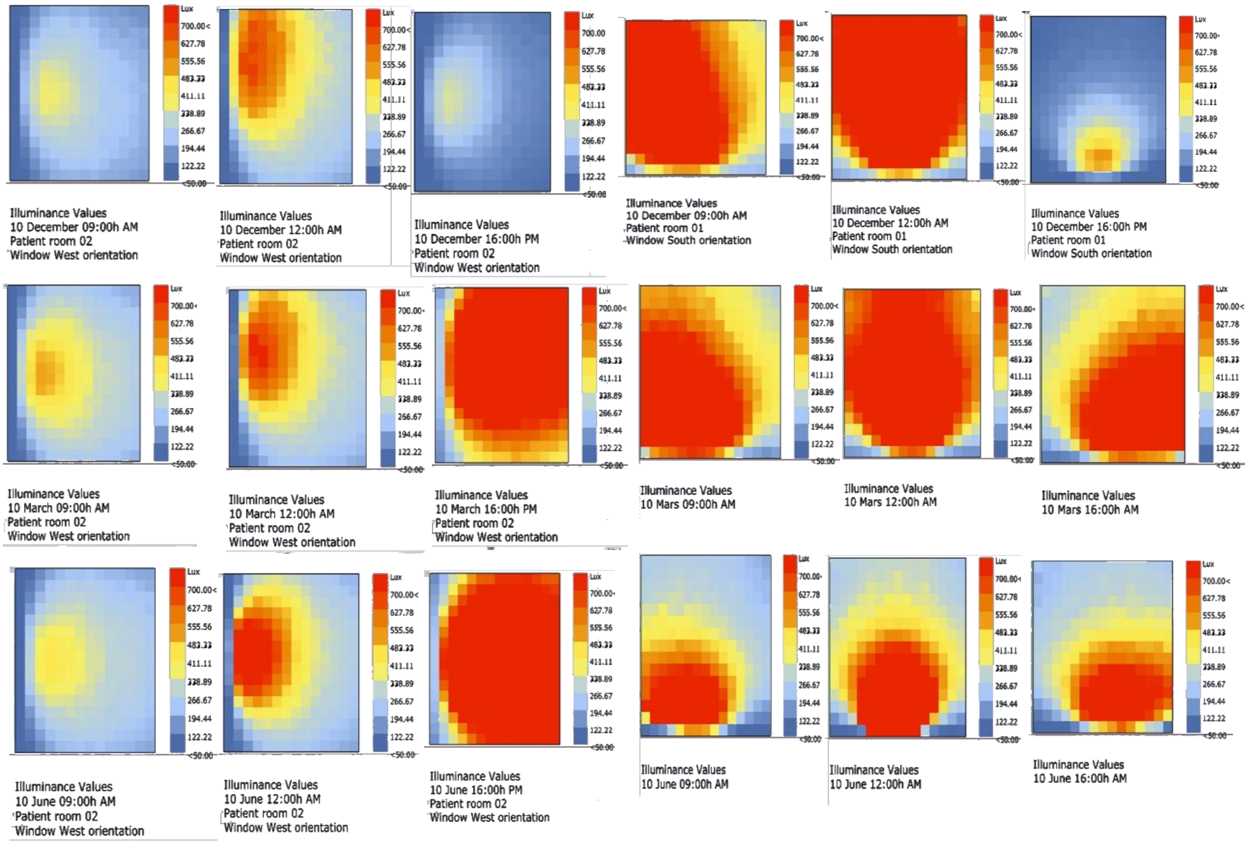


Figure 5.8: Illuminance values of the base case patient rooms
(Source: Author, 2021)

Conversely, in June, the average illuminance level surpasses 3000 lux, with values spanning from 200 lux to 3250 lux for West-oriented rooms. Meanwhile, in the month of March, the average illuminance level reaches approximately 1500 lux for West-facing rooms, showing fluctuations from 400 lux to 2500 lux in the West and exceeding 3000 lux in the South. These elevated illuminance levels can be attributed to the hot and arid climate. In terms of orientation, the initial room (South-facing) exhibits excessive illuminance levels during the morning period (from 9 am to 12 pm), in contrast to the other room (West-oriented). Similarly, the room with a West orientation experiences heightened illuminance levels (surpassing 2000 lux) during summer and spring, while during winter, the levels range from 300 to 1500 lux.

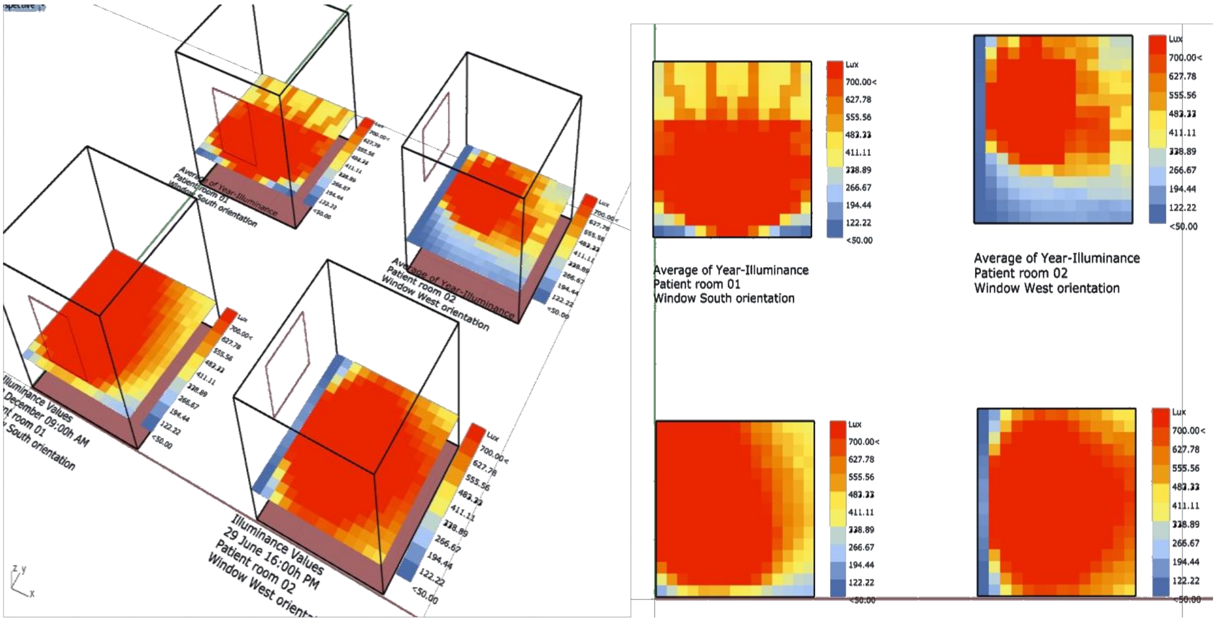


Figure 5.9: Average of year Illuminance values of the base case patient rooms (Source: Author, 2021)

The results obtained from the illuminance simulation indicate that during the morning, the overall illumination level exceeds the established norms for the closest points to the openings, but falls below the recommended values in the afternoon for the innermost regions of the indoor space in the winter and but the opposite in the summer. The patient chambers situated towards the southern and western aspects within the virtual environment showcase exceedingly intense illuminance levels. This could have an unfavorable influence on patients' well-being and lead to tiring situations characterized by excessive heat and discomfort due to glare.

5.4.3. Luminance results

This false color image displays an HDR image of a patient room case study with Diva- rhino plugin integrated with grasshopper + Rhinoceros illuminated by daylight. Towards referring to the provided legend, one can analyze the distribution of luminance throughout the scene. It is worth noting that the light source, represented by the sun, exhibits a relatively high luminance of 200,000 cd/m2, while the task area, represented by the windows, has a luminance of approximately 3000 cd/m2 (Au, P. P. Y., 2013). As seen in the Figure 5.10, Daily sun path orientation of patient rooms case study for the simulation of luminance in the design models. It depicted the each oriented room for simulation.

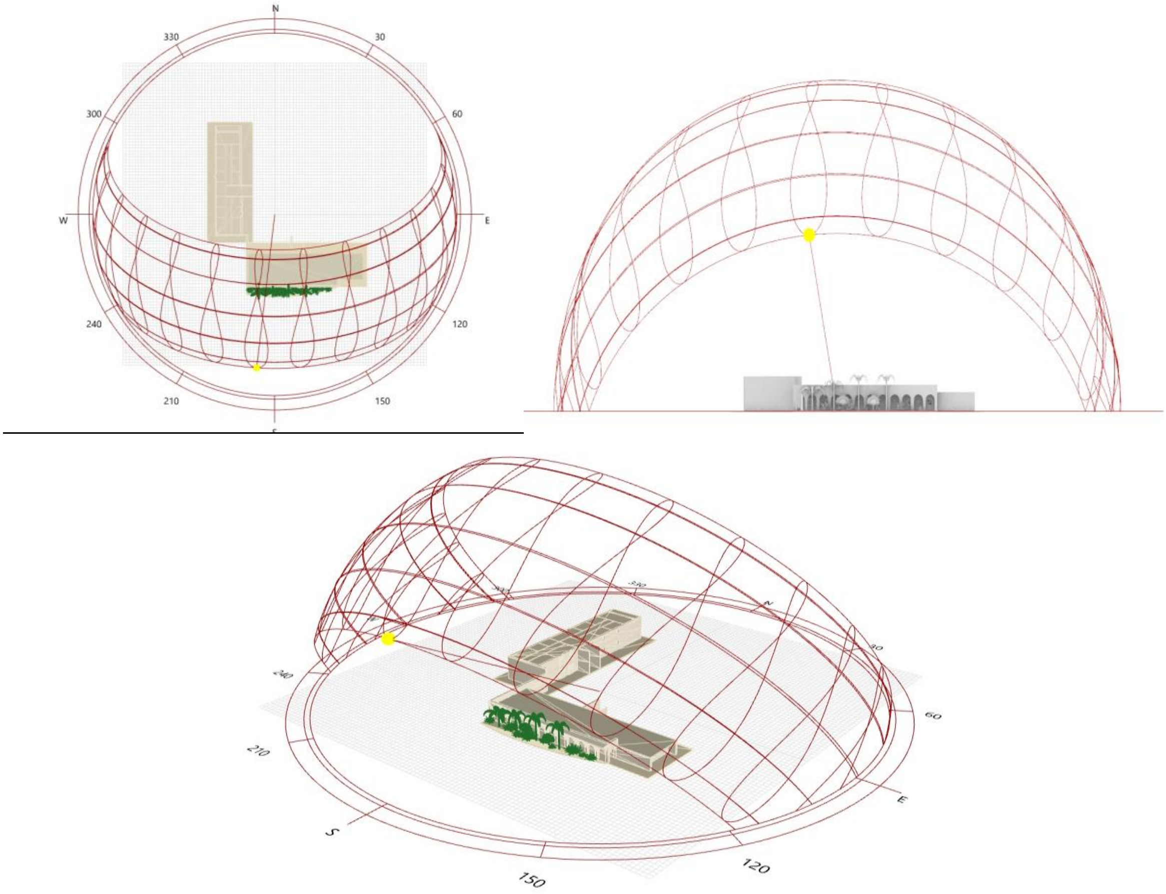


Figure 5.10: Daily sun path orientation of patient rooms case study
(Source: Author, 2021)

In the Figure 5.11, it described the falsecolor simulated images of luminance metric for three months in December, March and June over the three times in the day; at 9AM, 12 AM and 4 PM. The images created using Diva with Radiance simulation in Grasshopper software were devoid of fisheye lens distortion, which led to difficulties in directly comparing individual pixels between the actual and simulated data due to misalignment of geometric shapes. The image maps portray the range and patterns of luminance values, spanning from 3 to 300 cd/m² on the same scale, with peak luminance values exceeding >285 cd/m². Purple indicates areas with minimal luminance, measuring <3 cd/m², while yellow represents the brightest point, surpassing 9663 cd/m². This pronounced contrast arises from the noticeable differentiation between the windows and the interior recesses of the selected rooms.

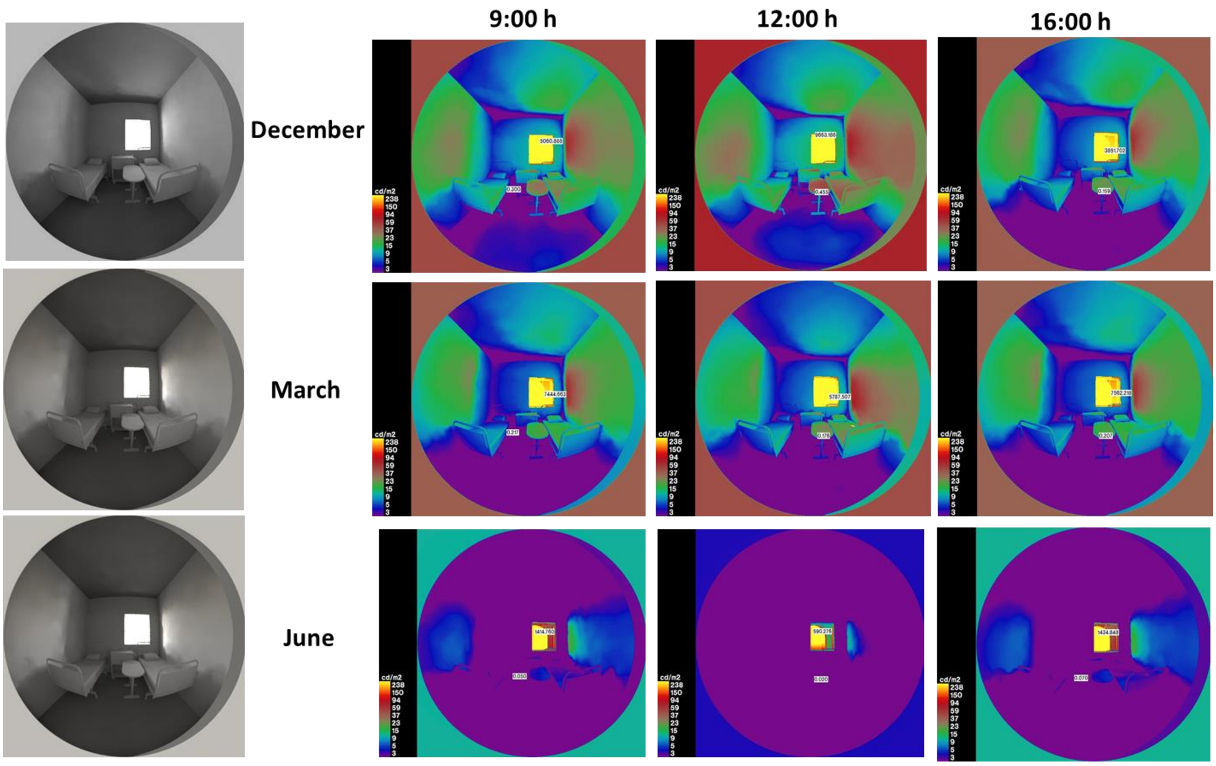


Figure 5.11: False color representation of a HDR image in Diva- for- Rhino
(Source: Author, 2021)

Consequently, the purple tones symbolize low luminance values (<3 cd/m^2), and the red tones indicate higher luminance values ranging from 700 to 9000 cd/m^2. However, a substantial portion of the area displays a deviation exceeding 30 cd/m^2 due to material misalignment in the software. When comparing the simulated luminance maps to the authentic HDR images captured on-site, it is evident that the simulated maps accurately predict glare in 62% of instances. This observation aligns with the findings of Jones and Reinhart. The outcomes indicate the luminance values in March and December, there are elevated luminance values spanning from 700 to 9000 cd/m^2, whereas in June, the values reach approximately 590 cd/m^2. This phenomenon can be explained by the lower solar altitudes during spring and winter in contrast to the heights observed in summer.

Despite of the geometric mismatch between the real and simulated images, the pixel-to-pixel comparison emerged as the least accurate approach among the four utilized. The incongruity in geometric shapes makes the comparison between the two images notably challenging and imprecise. Both images were transformed into false color renderings within Radiance, using identical luminance scales. An examination of the images produced was carried out through luminance map analysis to showcase the arrangement of luminance values.

Additionally, false color analyses were employed on the generated images to display the distribution of luminance ratios within the rooms, indicated by variations in color allocation.

Figure 5.12: Annual DGP profiles Discomfort Glare Probability (DGP)
(Source: Author, 2021)

The Figure 5.12 that represented above displays the annual Discomfort Glare Probability (DGP) profiles for the selected patient room. The horizontal axis represents the 365 days of the year, while the vertical axis represents the daytime hours from 8 a.m. to 6 p.m. Intolerable, disturbing, and perceptible glare are represented by the colors red, orange, and yellow, respectively, while imperceptible glare is indicated by green. The three patient rooms, have different orientation. The DGP profiles reveal that visual discomfort occurs more frequently during the winter months, particularly in the afternoon after 2 p.m., which aligns with the findings of the questionnaire. The comparison of the annual DGP profiles among the three patient rooms confirms that taller windows in Tier One contribute to a longer duration of annual glare.

5.5. Conclusion

The aim of this practical chapter was to establish a methodology for the current study based on the pilot study discussed in Chapter 4. This chapter is dedicated to elucidating the simulation workflow applied in the research. To begin, it introduces the design model for simulation, encompassing Grasshopper software, a parametric modeling tool employed for automating the daylighting simulation procedure, as well as the Diva for-Rhino plugin integrated with Radiance software to evaluate daylighting levels in patient rooms. Following this, it scrutinizes and assesses the simulation data, investigating the outcomes attained. Visual juxtapositions are drawn amid the optimized designs, concurrently delving into the augmentation of building performance and pinpointing the variables that wield the most substantial influence on the comprehensive performance of the building.

The simulation and validation study of performance offer numerous advantages in the realm of building design and optimization. It grants architects and designers the capacity to explore various daylighting strategies, assess their impacts on indoor environments, and make informed decisions in the early stages of design. Additionally, it opens avenues for energy optimization, as daylighting simulations aid in determining the most efficient utilization of artificial lighting systems, thus curtailing energy consumption. This field of research is in a constant state of advancement, driven by progress in simulation tools, data collection methods, and building performance assessment. Towards deepening our comprehension of how daylight interacts with architectural spaces, we can craft built environments that are more sustainable, comfortable, and aesthetically pleasing. The simulation and validation of daylight performance play a pivotal role in achieving these goals, contributing to the creation of buildings that are both healthier and more energy-efficient.

The introductory part of this chapter provides an outline of the simulation procedure employed to acquire illuminance and daylight levels on the patient room. It commences with a concise depiction of the parametric design model and the engines utilized in the simulation process, followed by an elucidation of the methodology employed for executing computer simulations. The subsequent part of the chapter delineates the design progression for the performance simulation step within the workflow. Lastly, the chapter delves into the validation phase, an essential stride to ascertain the accuracy of results, alongside the corresponding simulation outcomes.

CHAPTER 6

PARAMETRIC-BASED GENETIC ALGORITHMS OPTIMIZATION APPROACH TO COMPLEX DESIGN PROBLEMS: A NEW PARADIGM FOR ASSESSING DAYLIGHT

6.1. Introduction

Architecture functions as a complex adaptive system, both on the scale of individual buildings and as a system of design creation. Any alteration made to one part of a building can lead to unforeseen consequences on other components and systems within it. During the design process, architects must modify a building's design to cater to specific requirements, but each adjustment also affects the building's ability to fulfill other needs. Moreover, even after finalizing a design for one structure, architects often replicate and modify its elements for new projects. As time passes, successful innovative design elements contribute to the evolution of architectural styles. The current surge of interest in sustainability, which prompted the writing of this thesis, is undoubtedly a result of such a phase change, sending ripples throughout the architectural world.

Over the past few decades, building energy consumption has experienced a significant surge worldwide, and researchers predict a continuous upward trend (Yang, F., 2017). In light of the global energy crisis and the urgent need to address climate change, the focus has shifted towards developing high-performance and sustainable buildings, which has become a prominent research area today. The primary objective is to decrease energy consumption while ensuring the well-being and satisfaction of occupants within indoor environments (Yang, F., 2017; Nocera F. et al., 2018). Evaluating a building's energy performance requires comparing measured building metrics to reference values. One of the normalized metrics used for this purpose is Energy Use Intensity (EUI), which represents the energy consumed per square foot annually. It is calculated by dividing the building's total energy consumption over the year by its total floor area (Yang, F., 2017; Borgstein, E. et al., 2016). A lower EUI indicates superior building performance. Numerous internal and external factors impact a building's energy consumption, including weather data, schedules, and various building types, with some exhibiting higher EUI values compared to others (Yang, F., 2017).

When dealing with building design challenges, designers often face conflicting objectives, such as balancing energy demand reduction with maximizing daylight availability or thermal comfort. Genetic algorithms (GAs) have been frequently employed to address such architectural goals. Additionally, the utilization of parametric design in architecture has become more accessible and efficient, allowing for the simulation of numerous potential outcomes (Niclas, N.R., 2019). GAs function as computational models inspired by the theory of evolution. They initiate with a population of potential solutions, often determined by a random selection of specific parameters. To transition to the next generation of solutions, each individual's success determines its likelihood of being used to generate offspring for the subsequent generation.

Within this context, the upcoming chapter concentrates on advancing the modeling and simulation aspects of the multi-objective optimization for the selected model. The simulation models were created using the Grasshopper + Rhinoceros 6.0 software, employing the Ladybug, Honeybee 0.0.69, and Octopus plug-ins. Through the integration of parametric design and building performance evaluation tools, the system can generate design alternatives that align with specified design performance criteria. The initial section elaborates on the proposed process for optimizing building performance, which is seamlessly integrated into the schematic design phase – a crucial early stage in architectural design. The subsequent section illustrates the analysis outcomes and delves into the simulation of daylight performance. This investigation was conducted through a multi-objective optimization approach that aimed to minimize the Energy Use Intensity "EUI" while simultaneously maximizing the Spatial Daylight Autonomy "sDA" and Useful Daylight Illuminance "UDI."

6.2. Multi-objective Optimization research workflow

6.2.1. Design process based on the optimization algorithms

6.2.1.1. The overall Optimization Process in Grasshopper

In Chapter 5, a comprehensive overview was provided, presenting the simulation engines employed to carry out the annual dynamic simulations. Central to this process was the utilization of the Grasshopper + Rhinoceros 6.0 software, which played a crucial role as both a modeling and parametric design tool for optimizing daylight analysis and energy performance. The software's versatility and capabilities were enhanced by integrating several plugins, each serving specific purposes aimed at fulfilling the objectives of the study. The specific plugins integrated into the software were thoroughly discussed in the preceding chapter, elucidating their functionalities and contributions to the overall simulation framework. Honeybee possesses the capability to undertake a variety of simulation functions akin to those available in EnergyPlus, Radiance, and Daysim. The core principle underlying Honeybee is to streamline data input, simulation execution, and result visualization within a unified interface. Within this study, the geometric model's simulations harness Honeybee's algorithm to conduct comfort analysis, employing a fusion of microclimate maps and shading advantages to enhance the indoor comfort of occupants. Towards leveraging this integrated approach, the study could effectively explore and analyze various design options, allowing for the identification of optimal solutions in terms of daylight optimization and energy efficiency.

The term "algorithm" refers to a precise set of instructions typically given to a computer (Nathaniel L. J., 2009). Multiple algorithms can be devised to execute the process of the evolutionary mechanism. Each Genetic Algorithm (GA) combines various methods, such as translation, evaluation, selection, and variation, like interlocking puzzle pieces. Some methods work harmoniously together, much like well-fitting puzzle pieces, while others may not align as effectively. It's important to recognize that no single GA is universally suitable for every complex optimization problem. Thus, architects interested in optimization must be discerning in assembling an appropriate algorithm for the specific task at hand. The first step for this study is to select a suitable schema, representing the phenotype as a genotype as seen in Figure 6.1 below. When mutation alone introduces variation, the genetic information can be encoded in any order.

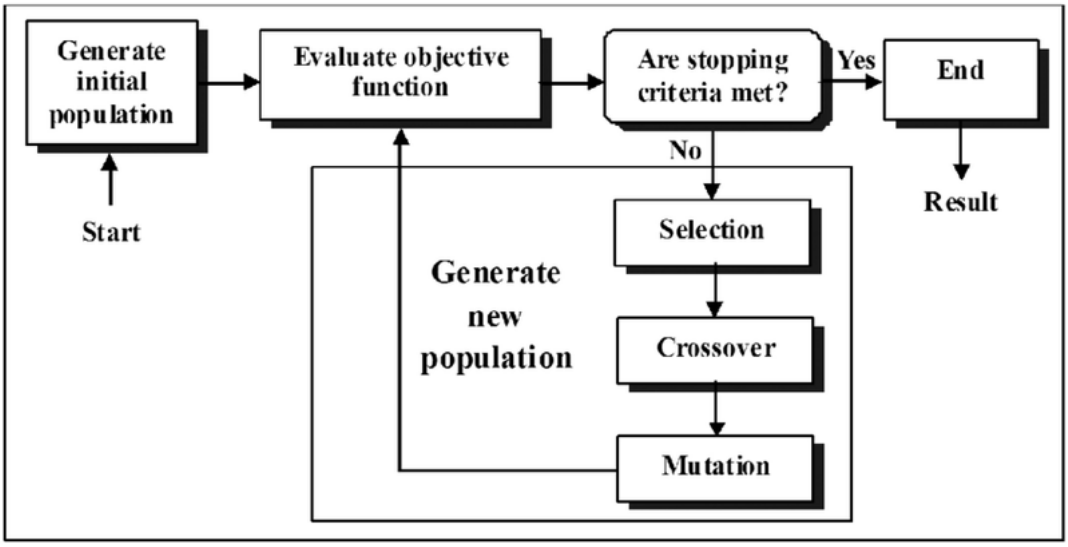


Figure 6.1: Basic Strucuture of Genetic Algorithm
(Source: www.skill-lync.com)

Depending on the representation of the genes and their significance, it may be beneficial for the architect to employ either integers or allow continuous parameter variation. GAs will exploit any advantageous discovery, including assumptions made by the programmer. Consequently, if the fitness is determined by an artificial valuation of competing goals or an arbitrary formula, GAs may capitalize on these aspects, even if they don't contribute to the desired outcome. Hence, it is crucial to ensure that the evaluation method is free from bugs and accurately reflects real-world selective pressures, as otherwise, it may assign high fitness values to solutions that prove to be futile. To achieve the design process as seen in Figure 6.2, offering a detailed representation of the workflow discussed earlier (for more details see Appendix D & E). At the core of this design process lies the Energy and Daylight Simulation module, which plays a crucial role in assessing and optimizing building performance. Within this module, the objectives of the samples, namely Energy Use Intensity (EUI), Spatial Daylight Autonomy (sDA), and Useful Daylight Illuminance (UDI), were meticulously determined (refer to Figure 6.3).

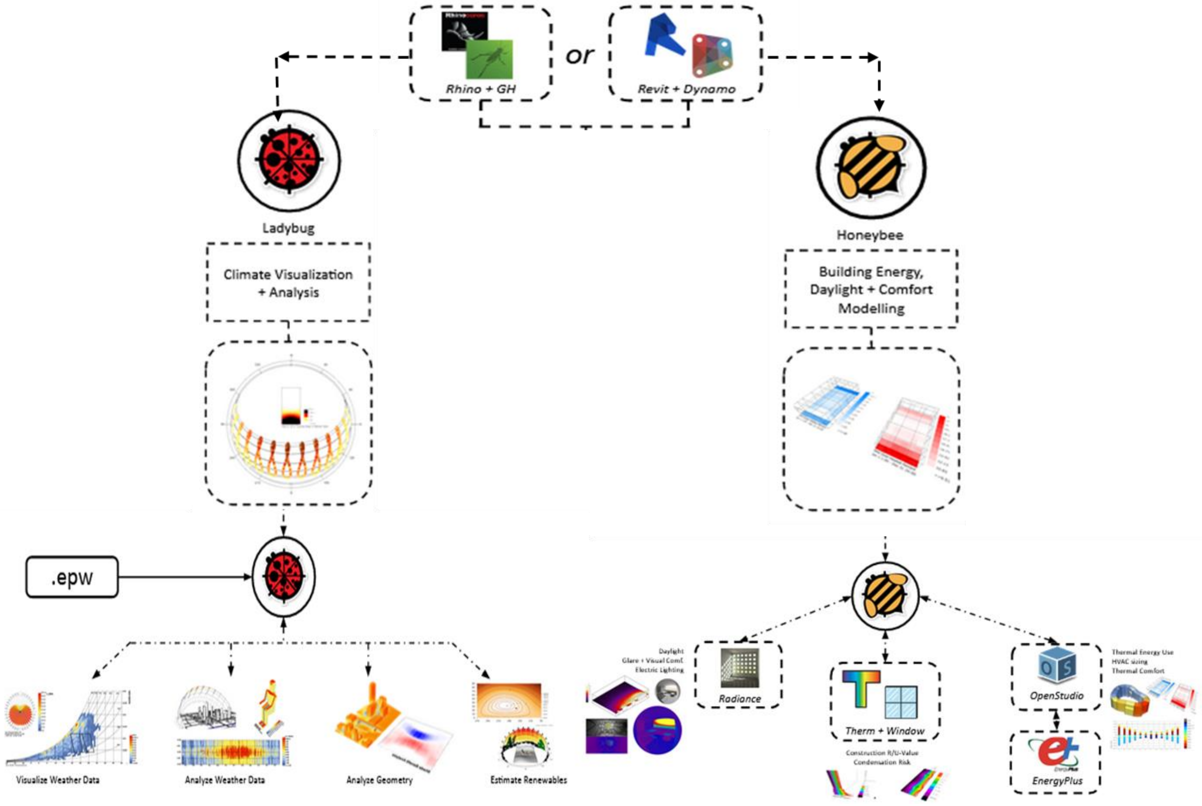


Figure 6.2: Honeybee & Ladybug Workflow and functions
(Source: Ladybug Tools website 2022)

This process was achieved by leveraging the capabilities of the Octopus plugin in combination with Pareto optimality theory and an evolutionary algorithm. Along with employing this innovative approach, the simulation framework successfully obtained optimal schemes and parameters that hold the potential to significantly enhance the energy efficiency and daylight performance of the designed structures. Subsequently, the outcomes and insights derived from this module were seamlessly integrated into the overall workflow design, offering valuable guidance and informing the decision-making process throughout the architectural design and optimization stages.

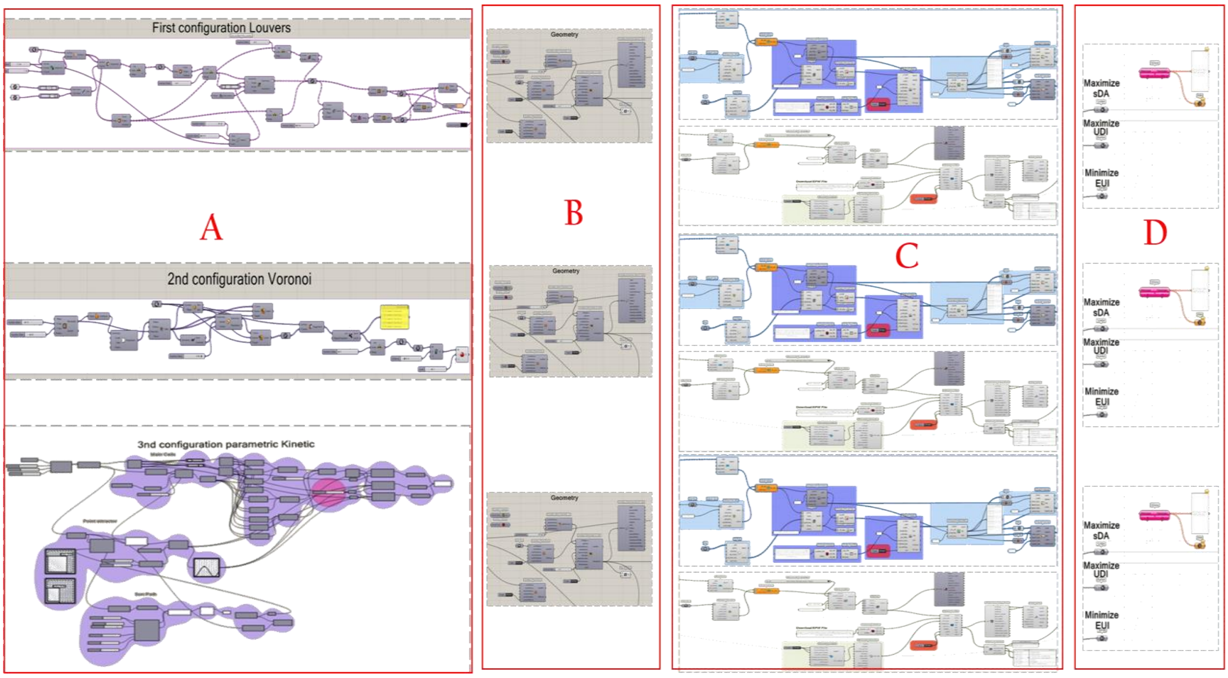


Figure 6.3: The overall algorithmic workflow process with Grasshopper Energy and Daylighting Simulation modules (Source: Author, 2021)

The complete research strategy and process can be visualized in Figure 6.3, which consists of four main steps. In the first step (A), the focus is identifying design parameters and constructing parametric design models. This involves creating three distinct models: the louvers design, the Voronoi configuration, and the Kinetic design. Moving on to the second step (B), the research entails developing the building geometry, which is then connected to the components in Group C. In this phase, daylight and energy modeling simulations are conducted for each of the three optimization configurations (see Figure 6.4, Figure 6.5 & Figure 6.6). The third step (C) involves the actual simulation process for daylight and energy performance, where the different building geometry configurations are put to the test. This step is crucial in assessing the potential impact of each design on factors like lighting levels and energy consumption. Finally, in the fourth step (D), the research focuses on data outputs. This involves employing specific components that facilitate the multi-objective optimization process. Than leveraging the Octopus plugin, the research aims to identify optimal solutions that achieve a balanced and efficient design, considering both daylighting and energy performance as essential objectives.

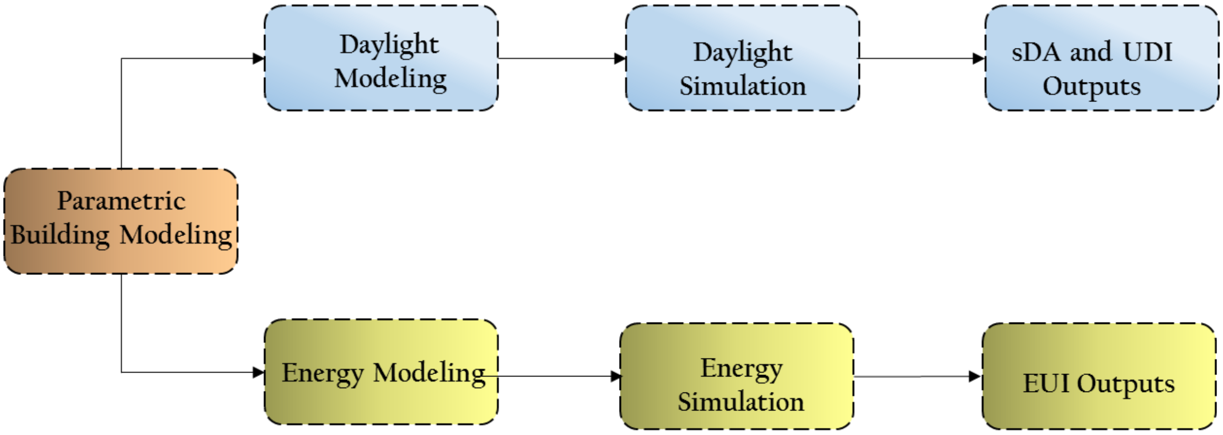


Figure 6.4: Integrated Daylight and Energy Simulation modules (Source: Author, 2021)

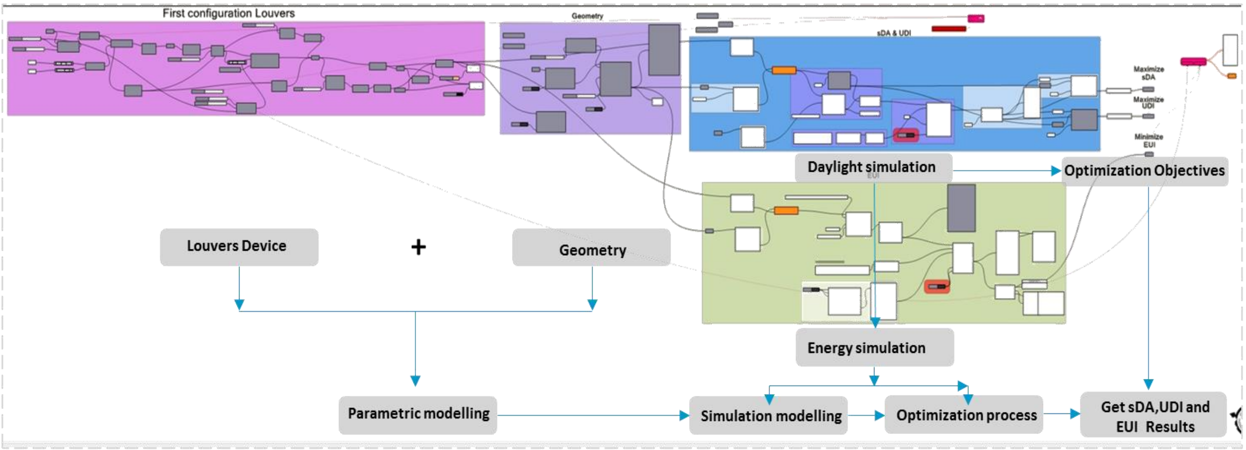


Figure 6.5: Algorithmic workflow process with Grasshopper Energy and Daylighting Simulation modules for Louvers design (Source: Author, 2021)

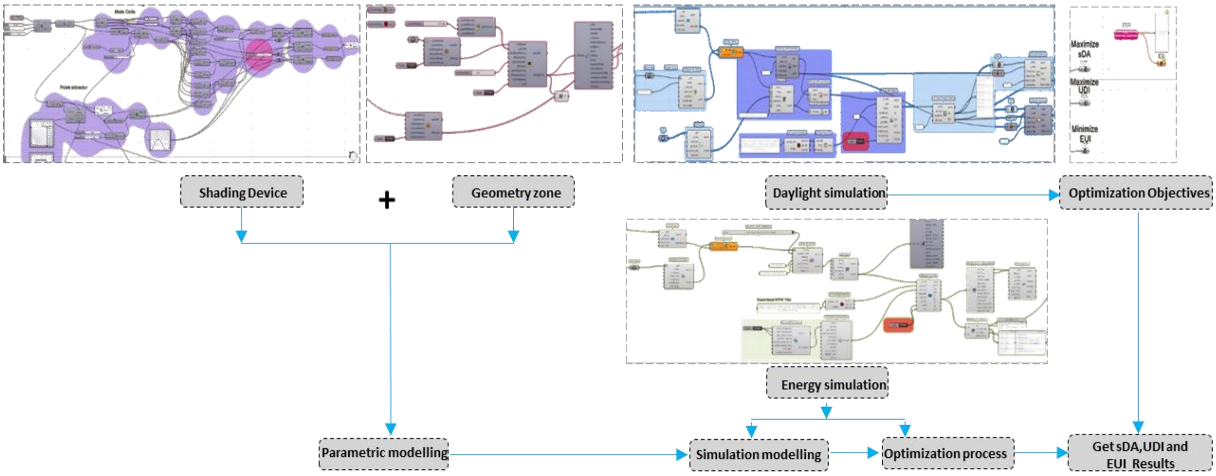


Figure 6.6: Algorithmic workflow process with Grasshopper Energy and Daylighting Simulation modules for Kinetic configuration (Source: Author, 2021)

Towards following this structured and systematic research strategy, the study seeks to uncover valuable insights into the impact of various design parameters on building performance. The integration of parametric design, simulation tools, and multi-objective optimization techniques ensures a comprehensive exploration of the design space, ultimately leading to the development of high-performance and sustainable building solutions.

6.2.1.2. Parametric modelling of Geometry

In the first step of this process, the research focused on the existing patient rooms within the Pediatric Ward, with the aim of addressing visual discomfort issues. To achieve this, geometric models representing three different configurations were created using Rhinoceros 3D 6.0 modeling software, integrated with Grasshopper (see Figure 6.7).

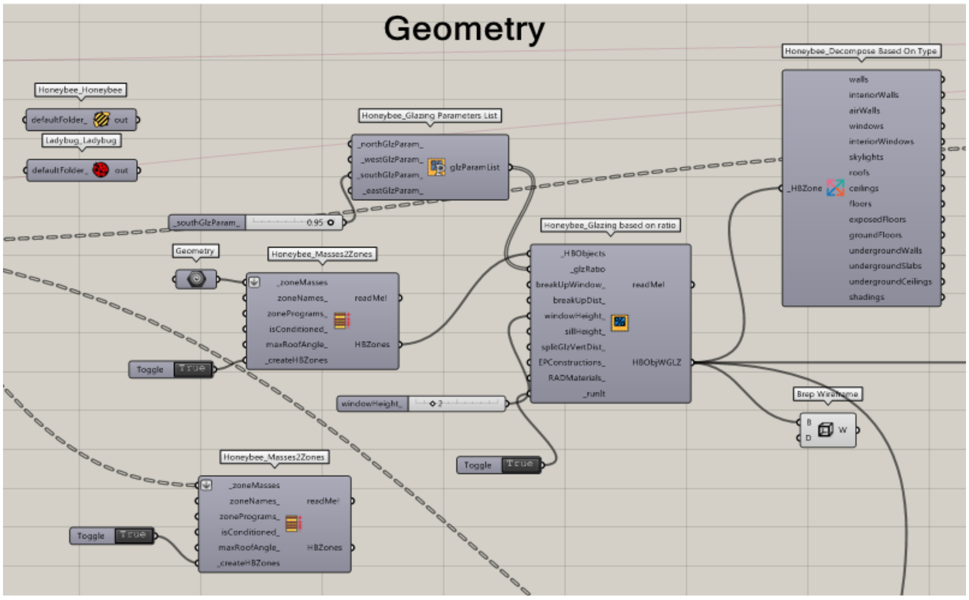


Figure 6.7: Algorithm components definition for developing the building geometry (Source: Author, 2021)

The investigation targeted the South orientation of the patient rooms, where field measurements indicated higher light values than the recommended levels in all three room cases. This indicated that patients in the rooms facing the South were more prone to experiencing excessive light and glare, leading to potential visual discomfort. To mitigate this problem and enhance patients' visual comfort, careful consideration must be given to the facade design features. Specifically, the implementation of sun-shading devices may be necessary in the patient rooms to effectively control glare and provide patients with an optimal visual environment. By strategically incorporating sun-shading solutions in the facade design, the excessive light and glare issues can be minimized, ensuring that patients in the Pediatric

Ward experience a more comfortable and conducive healing environment. The utilization of advanced modeling software and simulation tools enables architects and designers to assess different design options and determine the most effective sun-shading strategies to optimize the visual comfort of patients in these rooms.

6.2.1.3. Daylight and Energy algorithmic Simulations

In details according to the Figure 6.8, which illustrates a comprehensive and detailed algorithms optimization process of daylight performance as a sequent step. The process which begins within the Grasshopper environment, where parametric design variables and building geometry are established. The simulation functions for daylight and energy modeling are provided by Ladybug and Honeybee. During the daylighting modeling phase, the parametric building geometry is linked to the Radiance materials component. Hence, various material properties such as transparency and reflectance are configured. Subsequently, the building materials are connected to the daylighting simulation component. This step involves inputting essential parameters, including weather files, daylighting sensor placement, and other simulation settings. With these inputs, a Radiance (rad) file is generated, and the daylighting simulation is initiated within the Radiance software. Following the simulation, Ladybug facilitates the importation of the simulation results back into Grasshopper. The obtained data includes essential daylight performance metrics. Through the analyze of these metrics, the system generates an annual lighting schedule, providing valuable insights into the lighting conditions and variations throughout the year.

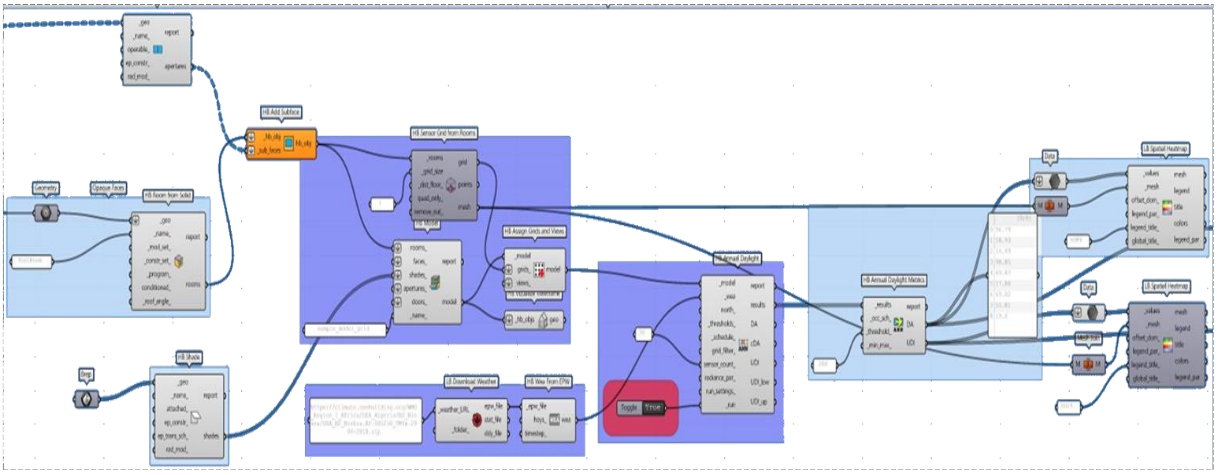


Figure 6.8: Daylight Optimization Process (Source: Author, 2021)

This comprehensive daylighting optimization process empowers architects and designers to make informed decisions and iteratively fine-tune their designs to achieve enhanced daylight performance and energy efficiency. The integration of parametric design, daylight modeling, and simulation tools facilitates a seamless workflow, fostering sustainable and high-performance building design.

Figure 6.9 depicts an elaborate energy optimization process, which shares a similar overall procedure with the daylighting optimization discussed previously. However, the key distinction lies in the optimization objective, which centers on minimizing the energy consumption of the building. To achieve this objective, the fitness input for the optimization is determined by the total energy load required for heating, cooling, and lighting. During the energy optimization process, design variables, daylighting metrics, and energy metrics are compiled and exported to another Excel file. This step facilitates a comprehensive analysis and comparison of various design scenarios, enabling architects and researchers to make informed decisions regarding energy-efficient design solutions.

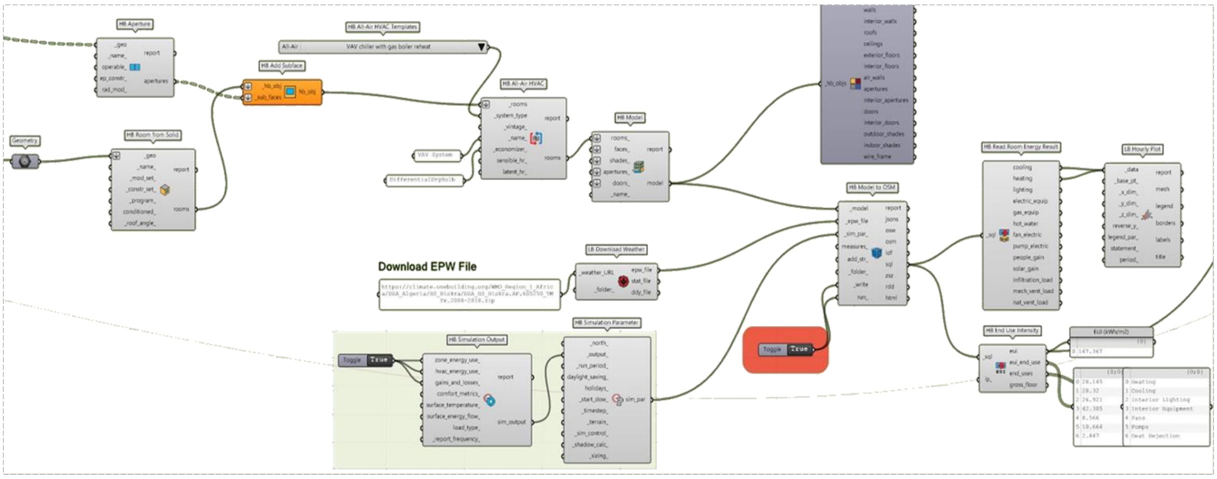


Figure 6.9: Energy Optimization Process (Source: Author, 2021)

The energy optimization process seamlessly integrates with the daylighting optimization, forming a holistic approach to building design that aims to strike an optimal balance between energy efficiency and daylight utilization. By leveraging parametric design, simulation tools, and advanced optimization algorithms, this process empowers designers to explore a vast design space, identify energy-efficient configurations, and ultimately contribute to the creation of sustainable and environmentally responsible buildings. The utilization of data-driven insights and real-time simulation results in the optimization process ensures that the proposed design solutions are not only energy-efficient but also responsive to the unique requirements and constraints of the building and its occupants.

6.2.1.4. Multi-Objective Optimization

The multi-objective optimization process shares similarities with the previously discussed optimization processes (see Figure 6.10), but it diverges in the choice of optimization engine capable of evaluating multiple objectives simultaneously. For this purpose, the Octopus plug-in, designed specifically for multi-objective optimization within Grasshopper, is employed to perform the optimization. The three primary objectives in this process are twofold: first, to minimize the Energy Use Intensity (EUI) and second, to simultaneously maximize both Spatial Daylight Autonomy (sDA) and Useful Daylight Illuminance (UDI).

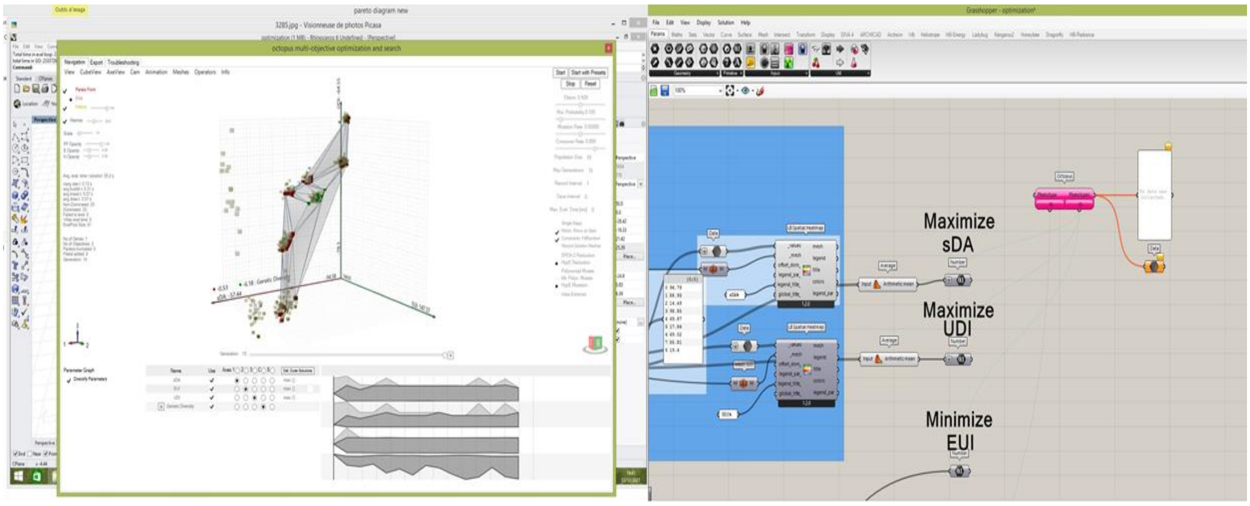


Figure 6.10: Multi-Objective Optimization Process and Tools

(Source: Author, 2021)

The overarching goal of this multi-objective optimization is to discover designs that strike a harmonious balance between daylighting and energy performance. In Octopus, the default behavior is to seek minimum values for each objective. However, as the average UDI is an objective to be maximized, it is multiplied by -1 during the optimization process. After executing the optimization, the Pareto frontiers are identified, representing trade-offs between each performance metric. These frontiers illustrate the optimal solutions that achieve a balanced compromise between daylighting and energy efficiency. By exploring this multi-dimensional solution space, architects and researchers gain valuable insights into the trade-offs and potential design directions, empowering them to make well-informed decisions and select designs that align with their specific goals and priorities. Ultimately, this multi-objective optimization process paves the way for the creation of buildings that exemplify exceptional daylighting, energy efficiency, and overall sustainability.

6.2.2. Input and Parameters adjusted during the optimization process

Once the configuration load and schedule variables were assigned, the study centered on the attributes of the current patient room in the Pediatric Ward. Parametric modeling simulation was then employed to design the geometry zone by modifying building construction materials, as previously discussed in details in the earlier chapter. Then, moving on parameters which adjusted during the optimization process, it was involved fine-tuning the optional combinations of parameters. As shown in **Table 6.1**, the parameters selected for the optimization process were carefully chosen due to their potential to significantly impact building performance simulations.

Table 6.1: Parameters integrated during the optimization process of the configuration model (Source: Author, 2021)

Decision variables	settings	Range
Glazing ratio	Double glazed low-E (vacuum)	90°
Glass type material	Double glazed low-E (vacuum)	[0 ,1 , 2][a]
Wall's materials	Double red brick with Isolation	1
The adaptive parameters	Module Radiance Material	[0 , 1][b]
	Modules rotating angle	[0 – 90°]
	Module distance to glass	[1 – 50 cm]
	Sun's position angle	[0 – 180°]

[a] 0: Double pane-low emissivity with 64%; 1: Double pane-clear with 80% ; 2: Single pane clear with 86%.
[b] 0: Metal; 1: Plastic.

As a result, certain parameters required manual adjustments, as outlined in detail below. To carry out the optimization, a multi-objective approach was employed, facilitated by the utilization of the Octopus plug-in, which seamlessly integrated these variables. The variables were divided into two distinct categories:

- Fixed adjusting parameters: This category encompassed the glazing ratio, glass type material, wall construction materials, and external kinetic module material. These parameters remained unchanged throughout the optimization process, serving as constants during the iterative exploration.
- Adaptive adjusting parameters: In contrast, the second category involved parameters that were subject to adaptation and modification during the optimization process. These included the modules' rotating angle and width, module distance to the glass, and the sun's position angle axis. The adaptive adjustments were made based on day,

month, and hour inputs, allowing for dynamic optimization in response to varying environmental conditions.

Towards the integrating these selected variables and leveraging the capabilities of the Octopus plug-in, the study embarked on a comprehensive multi-objective optimization journey. The primary goal was to strike an optimal balance between various building performance metrics, such as energy efficiency, daylight utilization, and overall occupant comfort. The iterative exploration of these parameter combinations allowed the research team to identify and refine solutions that exhibited superior performance across multiple criteria, thereby contributing to the advancement of high-performance and sustainable building design.

6.2.3. The three parametric optimized types of configurations

6.2.3.1. Kinetic design

The research focused on improving the patient rooms in the Pediatric Ward by addressing visual discomfort caused by excessive light and glare. To achieve this, a Kinetic configuration, a generative performing facade design, was developed using Rhinoceros 3D modeling software. This design approach was implemented in the southern orientation of the building, where field measurements had shown higher light values than recommended for patient comfort. The study revealed that patients in the southern-facing rooms experienced more exposure to excessive light and glare. Therefore, careful consideration was given to incorporating facade design features, particularly sun-shading devices, to enhance visual comfort for the patients. As seen in Figure 6.10 and Figure 6.11, depict the evolution of the facade geometry, demonstrating different kinetic configuration states and how responsive modules can rotate from 0° to 90°. The adaptive behavior of these modules allowed each hexagonal cell on symmetrical axes to rotate based on the sun's position, employing a parametric algorithm. The primary objective of this configuration was to create a responsive shading solution for patient rooms, specifically addressing completely glazed southern-facing rooms with a 90% window-to-wall ratio (WWR).

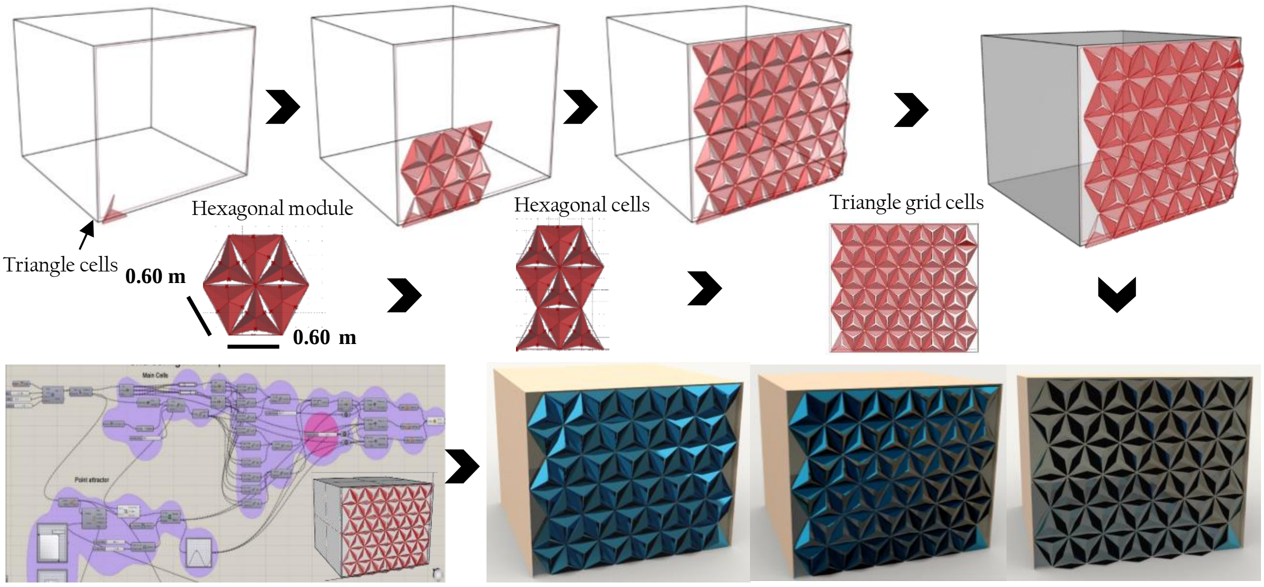


Figure 6.10: Parametric modelling facade development, Kinetic configuration render in Rhinoceros & grasshopper software (Source: Author, 2021)

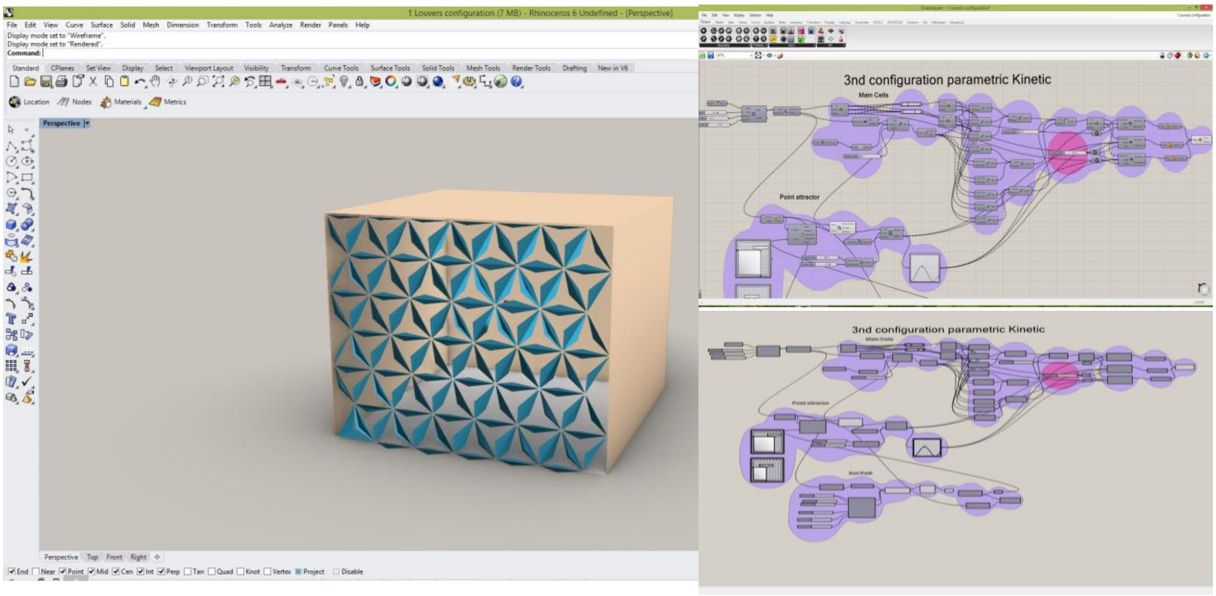


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Figure 6.11: Kinetic configuration render in Rhinoceros & grasshopper software (Source: Author, 2021)

Furthermore, the design was intended to be versatile enough to be applied to various building orientations. By adopting the kinetic facade design, the researchers ensured that the patient rooms received sufficient indoor daylight without discomforting glare. This "smart" facade automatically adjusted the modules to follow the sun's position, creating effective shade and optimizing the indoor environment for patient well-being.

6.2.3.2. Louvers configuration

As seen in the Figure 6.12, this illustration elaborates on the parametric modeling approach applied to the development of the second selected configuration for the Louvers design. Within this innovative design, a gracefully curved surface is established through the strategic manipulation of two attractor points.

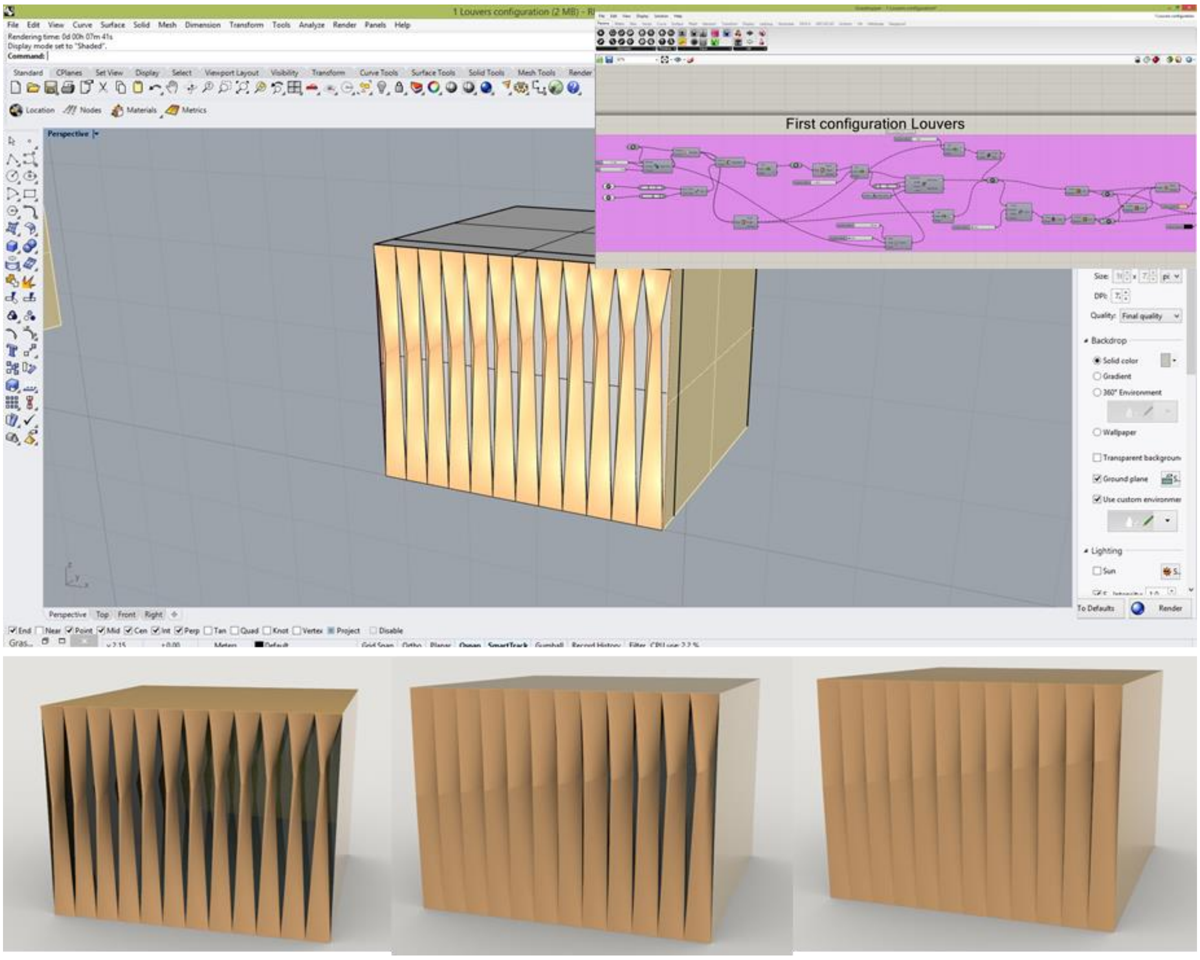

Figure 6.12: Parametric modelling facade development, Louvers configuration render in Rhinoceros & grasshopper software (Source: Author, 2021)

These points act as influencers, guiding the displacement of the surface by utilizing diverse graphical representations such as linear, curved, or sinusoidal patterns. Crucially, the positioning of these attractor points, the extent of displacement, and the specific graphical pattern employed can all be precisely managed through adjustable parameters. The resulting contoured surface is then meticulously segmented, giving rise to a series of horizontal divisions that collectively shape the creation of windows. The interstices between these divisions allow the seamless passage of natural light. Remarkably, behind this meticulously crafted facade lies a continuous expanse of glass, diverging from traditional window construction. The variables governing the number of horizontal divisions, as well as the upper and lower bounds of their dimensions, are subject to parameter control. This intriguingly enables the deliberate skewing of divisional lines in either direction, affording the ability to selectively block light from either the left or right side of the interior space.

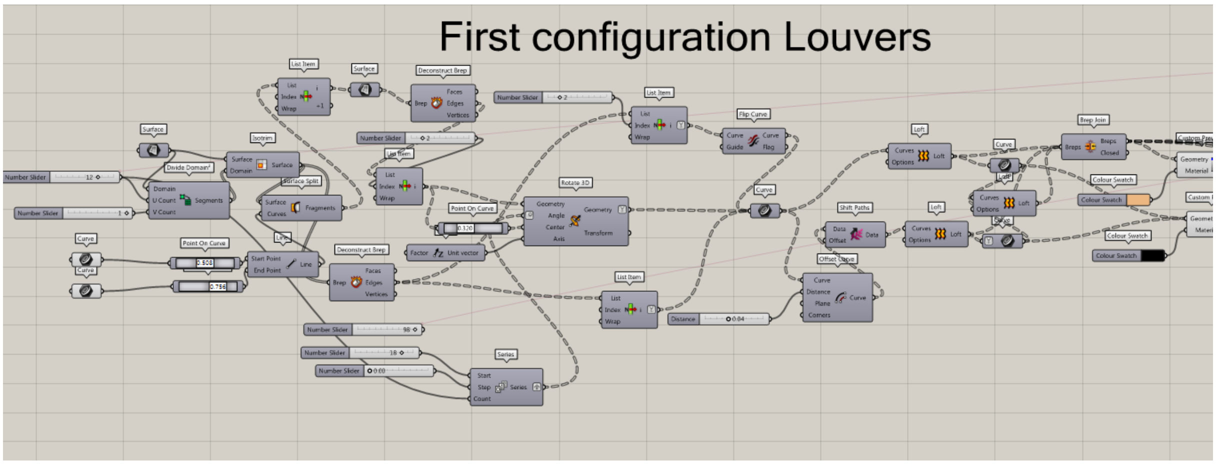

Figure 6.13: Algorithmic definition of Louvers configuration (Source: Author, 2021)

This architectural blueprint opens the door to a plethora of captivating design possibilities. Beyond its influence over window attributes, the design also encompasses the curvature of the facade itself. When combined with the segmentation of the horizontal divisions, this amalgamation offers an unparalleled degree of mastery over the angle at which sunlight interacts with the structure. As a result, an extensive spectrum of design scenarios can be realized, ranging from intricately ordered compositions to more organic and complex arrangements. This versatility imbues the design with an extraordinary degree of potency, underscoring its potential to transform spaces in profound ways.

6.2.3.3. Voronoi configuration

As seen in Figure 6.14, this architectural concept draws its inspiration from Voronoi tessellation, a form of stochastic pattern generation characterized by the creation of a set of randomized points. These points then serve as the epicenters around which distinct regions emerge, their boundaries delineated by distance-based considerations. In the context of this design, these delineated regions take on the role of windows. In stark contrast to the previous design, this approach introduces an organic, less regimented aesthetic to window sizes and arrangement. The control mechanisms that govern this design are akin to those employed in the earlier iteration. However, they now operate in a manner that embraces a more naturally evolving disposition.

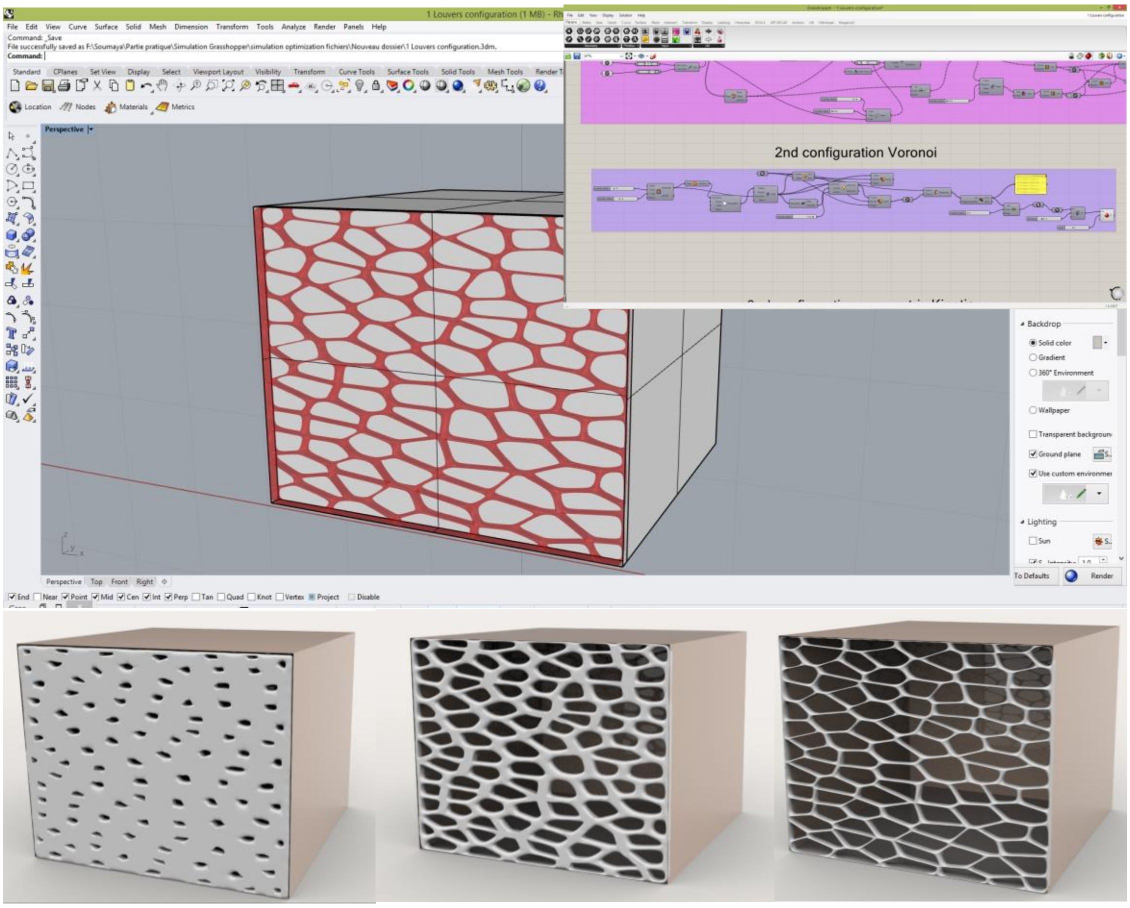

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Figure 6.14: Parametric modelling facade development, Voronoi configuration render in Rhinoceros & grasshopper software (Source: Author, 2021)

The parameters under scrutiny encompass two primary facets: the quantity of points earmarked for distribution within the Voronoi tessellation, and the dimensions of the resultant regions they generate. Moreover, the intricacies of this design flourish with the strategic integration of two attractor points. These points inject a layer of complexity into the Voronoi tessellation, fostering the creation of regions characterized by heightened density. Paramount among these design considerations are the precise positioning of these attractor points, along with the influence they wield over the radius of the regions they shape – all artfully regulated through the established parameters.

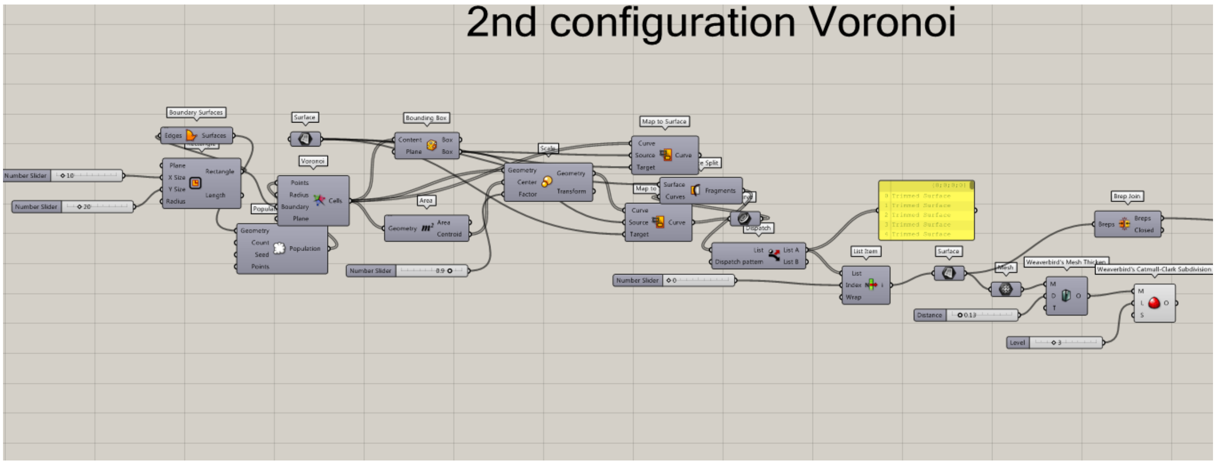

Figure 6.15: Algorithmic definition of Voronoi configuration (Source: Author, 2021)

Fundamentally, this design surpasses the conventional boundaries of a mere architectural plan, encapsulating a dynamic interaction between regulated variables and the evolving shape it engenders. Towards harmonizing the blend of randomness and structure inherent in Voronoi tessellation, coupled with the deliberate arrangement of attractor points, a fresh and captivating architectural expression emerges. This expression seamlessly fuses the intrinsic elegance of nature with the precision of innovative design, forging a distinctive architectural narrative.

6.3. Results and discussion

6.3.1. The Optimized model simulation results

6.3.1.1. Optimization objectives

The primary objective of this research was to decrease building energy consumption while simultaneously ensuring optimal indoor daylight quality. This pursuit is particularly critical in regions characterized by intense heat and aridity, where a dilemma arises due to the conflicting nature of energy consumption and daylight quality. The research aims to reconcile this inherent contradiction between daylighting and energy efficiency. In this context, a prevalent approach involves reducing the Window-to-Wall Ratio (WWR) parameter to curtail energy usage. However, this approach tends to compromise indoor daylight quality. Importantly, the introduction of natural daylight into indoor spaces profoundly impacts occupants' well-being, a factor of utmost significance, especially in sensitive settings such as hospitals, where patient well-being is paramount.

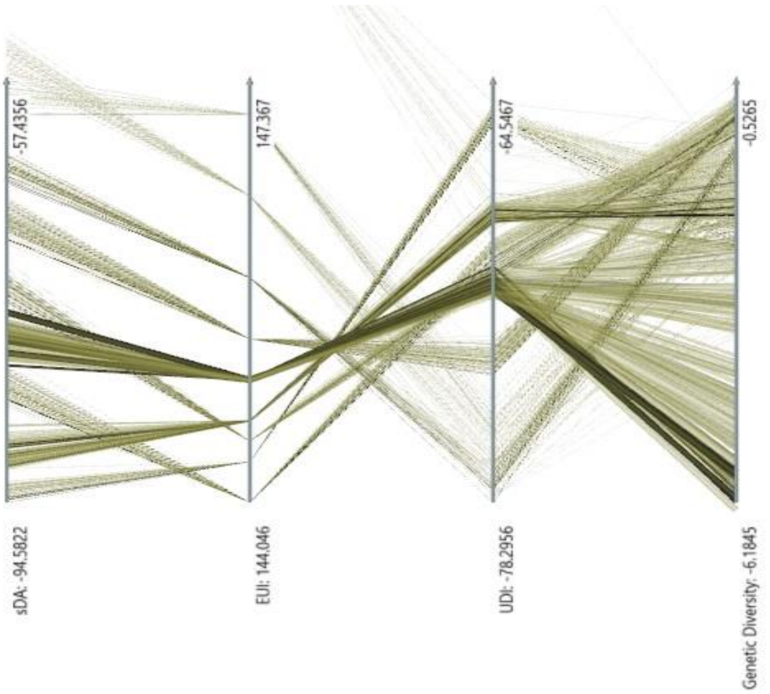

Figure 6.16: Objectives diagram of Pareto front in a parallel coordinate plot

(Source: Author, 2021)

Thus, within this study, the optimization goals encompassed three key aspects: first, minimizing Energy Use Intensity (EUI) to enhance energy efficiency; second, maximizing Spatial Daylight Autonomy (sDA) to ensure ample daylight availability; and third, maximizing Useful Daylight Illuminance (UDI), a measure of the quality of daylight, as depicted in Figure 6.15. These objectives align with the overarching aim of striking an optimal balance between energy efficiency and indoor daylight quality, particularly in environments like hospitals where the well-being of occupants is intricately linked to these factors.

6.3.1.2. The objective function

An analytical exploration was carried out through a multi-objective optimization framework to evaluate various architectural design elements. This assessment utilized Spatial Daylight Autonomy (sDA), Useful Daylight Illuminance (UDI), and Energy Intensity Use (EUI) as primary indicators for daylight and energy efficiency. The objective function, a fundamental component of optimization problems, was derived from a Pareto Front diagram generated using the Octopus tool. This process aimed to comprehensively analyze and enhance both daylight and energy performance within building designs.

The objective function stands as a fundamental principle in the realm of mathematical optimization and engineering. It serves as a mathematical representation that outlines the objectives or aims of an optimization challenge (Konis, K. S., 2012; Peri, D. et al. 2020; Fatma

Mohamed A., 2016). This function typically takes shape based on the variables and parameters inherent to the problem, effectively gauging the excellence or effectiveness of a solution with respect to desired outcomes. Within the optimization context, the significance of the objective function is paramount, steering the optimization algorithm towards unearthing the most optimal solution within a specified set of constraints. The ultimate objective involves identifying input values for the variables, either maximizing or minimizing the objective function, contingent upon whether the problem centers on maximizing gains or minimizing losses. To illustrate, consider the scenario you provided: the objective function was harnessed to evaluate distinct building design attributes, encompassing Spatial Daylight Autonomy (sDA), Useful Daylight Illuminance (UDI), and Energy Intensity Use (EUI). Through mathematical manipulation, this objective function amalgamates these metrics, thus encapsulating the comprehensive daylight and energy performance of the building's design. Consequently, the optimization process strives to pinpoint the most favorable design parameters that strike an optimal balance or trade-off between these indicators of performance. In summation, the objective function undertakes a pivotal role in the realm of optimization challenges, functioning as a quantifiable gauge that expertly directs the pursuit of an optimal solution, all while scrutinizing the performance of varied amalgamations of parameters (Toutou, A.M.Y., 2019; Zhang, L. et al., 2016; Yang, F., 2017).

As stated by Konis et al. (2012), as seen in the fitness function Equation (6.1) which provided the means to accurately attain optimal outcomes within the Pareto front framework. In this context, the research objectives encompass SDA, UDI, and EUI. Notably, the primary aim is to maximize the first two objectives while simultaneously minimizing the third.

$$y = (sDAi - sDAmin)C1 - 1(EUIi - EUImin)C2 + (UDIi - UDImin)C3 \qquad (1)$$

Where: *i*: result of iteration, *min:* minimum value of optimization set and *max:* maximum value of optimization set. In addition:

$$C1 = \frac{100}{(sDAmax - sDAmin)},$$

$$C2 = \frac{100}{(EUImax - EUImin)},$$

$$C3 = \frac{100}{(UDImax - UDImin)}$$

In this study, the values of the objective function were calculated of some solutions in the Pareto front diagram as shown in Table 6.2 (see the next section 6.3.1.3), which represent the optimum solutions for the performance of daylighting and energy performance. Where the results of C1, C2 and C3 respectively are:

C1 = 2.60, C2 = 30.10, C3 = 7.27

Table 6.2. Fitness function values and their characteristics of Pareto Front optimum Solutions (Source: Author, 2021)

Y	sDA %	UDI %	EUI KWH/ $m^{2/}$year	Wall construction	Glass material	Shading device		
						Width	Count	Angle
90.8	94.3	64.9	144.3	Double brick with air cavity	Double glazed low-E (vacuum)	0.20	12	- 45°
87.8	94.3	64.9	144.4	Double brick with air cavity	Double glazed low-E (vacuum)	0.20	11	- 45°
94.2	91.0	68.2	144.7	Double brick with air cavity	Double glazed low-E (vacuum)	0.19	12	- 45°
94.5	91.1	68.2	144.7	Double brick with air cavity	Double glazed low-E (vacuum)	0.19	12	- 45°
92.6	90.0	68.3	144.6	Double brick with air cavity	Double glazed low-E (vacuum)	0.19	12	- 30°
99.5	84.7	69.6	144.0	Double brick with air cavity	Double glazed low-E (vacuum)	0.16	11	- 30°
99.6	83.7	69.9	144.0	Double brick with air cavity	Double glazed low-E (vacuum)	0.15	12	- 30°
97.6	90.6	70.5	145.1	Double brick with air cavity	Double glazed low-E (vacuum)	0.18	12	- 30°
69.4	81.4	69.9	145.1	Double brick with air cavity	Double glazed low-E (vacuum)	0.16	12	- 30°
62.8	76.3	70.8	145.1	Double brick with air cavity	Double glazed low-E (vacuum)	0.14	12	- 25°
50.6	69.3	72.9	145.4	Double brick with air cavity	Double glazed low-E (vacuum)	0.12	11	- 15°
51.5	68.0	73.5	145.4	Double brick with air cavity	Double glazed low-E (vacuum)	0.10	12	- 15°

6.3.1.3. Pareto Front scheme and Optimal Solutions

Pareto optimization, as elucidated by Yuan Fang (2012), involves the determination of a balanced front among multiple objectives, commonly known as the Pareto front diagram (Thomas R., 2005). In the pursuit of an analytically qualified optimal Pareto solution, numerous generations of genomes (solutions) must be generated. Within the scope of this study, depicted in Figure 6.17, a total of 15 generations were produced, each subsequent generation comprising 50 genomes with higher fitness compared to its predecessor. This visual representation clearly exhibits incremental enhancements with each successive generation, particularly evident in the values of sDA, UDI, and EUI. Consequently, the objective function, a reflection of these improvements, experiences corresponding augmentation.

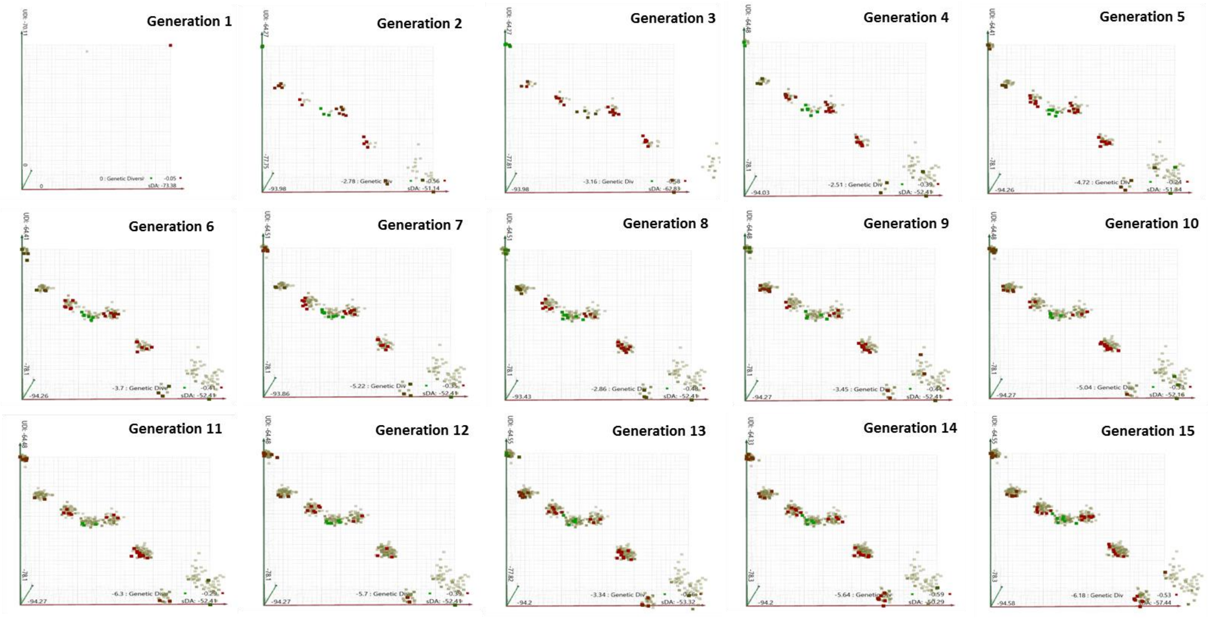

Figure 6.17: Pareto Front diagram of 15 Genomes generations produced in Octopus plugin Grasshopper software (Source: Author, 2021)

The fitness values (Y values) of the optimal solutions across the 15 generations, arranged in descending order, are as follows: 99.6, 99.5, 97.6, 94.5, 94.2, 92.6, 90.8, 87.8, 69.4, 62.8, 51.5, and 50.6. Notably, the initial generation exhibited maximum sDA and UDI values of 73.38 and 70.11, respectively, which significantly escalated to 94.58 and 78.30 in the final generation. In contrast, the minimum EUI value, starting at 158.2 Kwh/m²/year in the first generation, underwent substantial reduction, culminating in an optimal energy consumption value of 144.05 Kwh/m²/year in the concluding generation.

Following a comprehensive optimization search spanning 15 generations, the Pareto front chart (depicted in Figure 6.18 & Figure 6.19) displayed a clear convergence trend within the final generation's 50 non-dominated solutions. This visual representation adopts a 3D scatter plot format, with sDA, UDI, and EUI respectively positioned along the x, y, and z axes. The transparency-modulated squares within the Pareto diagram symbolize earlier generations, becoming progressively darker to denote escalating iterations. Solutions marked within red squares are non-dominated, signifying optimal outcomes, while green squares represent dominated solutions [15,17].

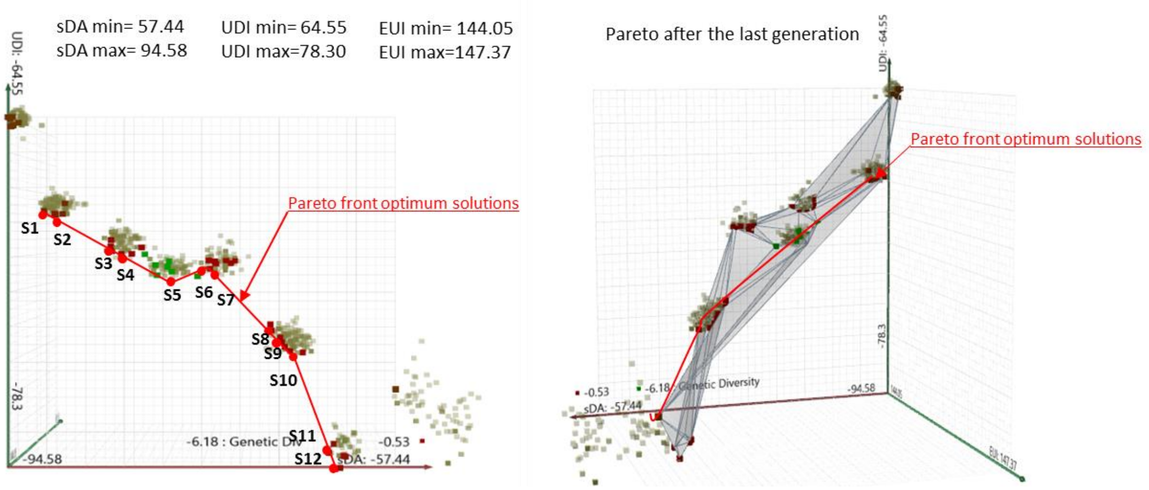

Figure 6.18: Development of optimum solutions in Pareto Front diagram after the last generation (Source: Author, 2021)

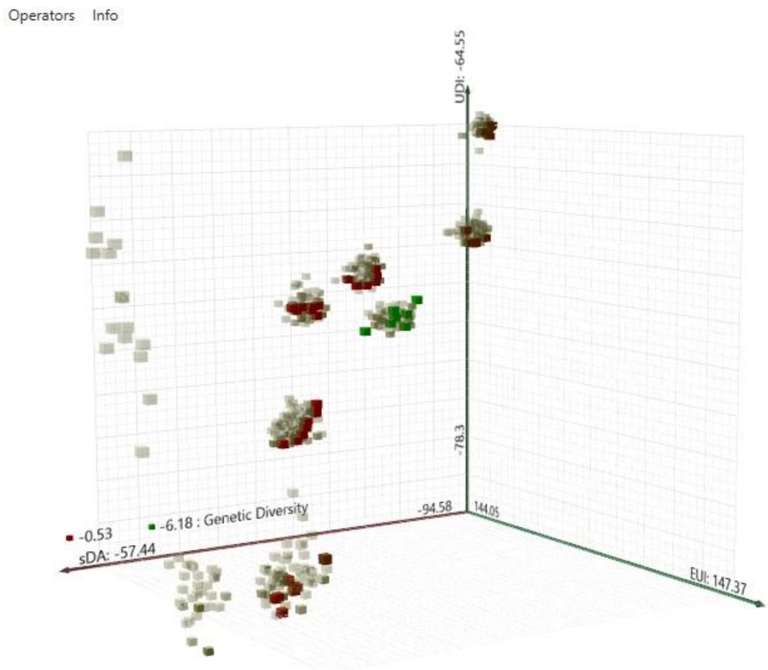

Figure 6.19: Pareto Front diagram after the last generation (Source: Author, 2021)

The most favorable solutions are situated closest to the chart's center. A noteworthy advantage of the genetic algorithms optimization process is revealed, as it significantly contributes to addressing multi-objective challenges. Consequently, non-dominated solutions boasting heightened sDA and UDI values indicate an upward trajectory in outcomes, juxtaposed with a declining trend in EUI results. This dynamic portrayal underscores the central objective of the Pareto chart: the quest for harmoniously balanced design alternatives that amplify daylight performance while curbing energy expenditure. Table 6.2 offers a selection of solutions gleaned from the nearest non-dominated alternatives, representing diverse optimized scenarios. Each of these Pareto optimal front solutions is meticulously assessed, with their corresponding objective fitness functions meticulously calculated and detailed, encompassing all pertinent parameters and simulation findings.

6.3.1.4. The absolute optimum solution

The optimal solution, relatively speaking, was meticulously chosen from the collection of non-dominant solutions, distinguished by its remarkable achievement in balancing and excelling across the three specified objectives. This selection garnered the highest score in the fitness function (**Toutou, A.M.Y, 2019**), as illustrated in Table 6.2, attaining an exceptional fitness value of 99.6 (identified as solution 7). In the final generation, substantial enhancements were achieved for sDA, UDI, and EUI. The sDA and UDI metrics reached percentages of 83.7% and 69.9% respectively, though slightly below the ideal values for optimal daylighting. In contrast, the energy use intensity reached its nadir at 144.0 Kwh/m^2/year within the optimal EUI context. Figure 6. 20 presents a comprehensive examination of daylighting across three distinct parametric modules, encompassing unresponsive and responsive positions, which pivot upon solar angles and orientation parameters. The findings underscore the significant capability of an attached three types of configurations (Louvers, Voronoi and Kinetic configuration) to considerably diminish direct sunlight penetration, particularly during occupied periods. Furthermore, this configuration adeptly sustains indoor daylight levels beyond 50% across the work plane, surpassing the performance of an unshaded facade. The adaptability of this mechanism to automatic control based on solar angles and orientations accentuates its potential to substantially enhance the daylighting experience for patients. As a result, this parametric configuration holds the promise of effectively generating patient room designs that prioritize effectiveness and provide ample and comfortable daylighting conditions. Essentially, this parametric approach facilitates the generation of patient room designs that are both efficacious and capable of providing ample and comfortable daylighting conditions. The inherent adaptability of the system based on solar dynamics underscores its potential to significantly contribute to patient well-being and comfort.

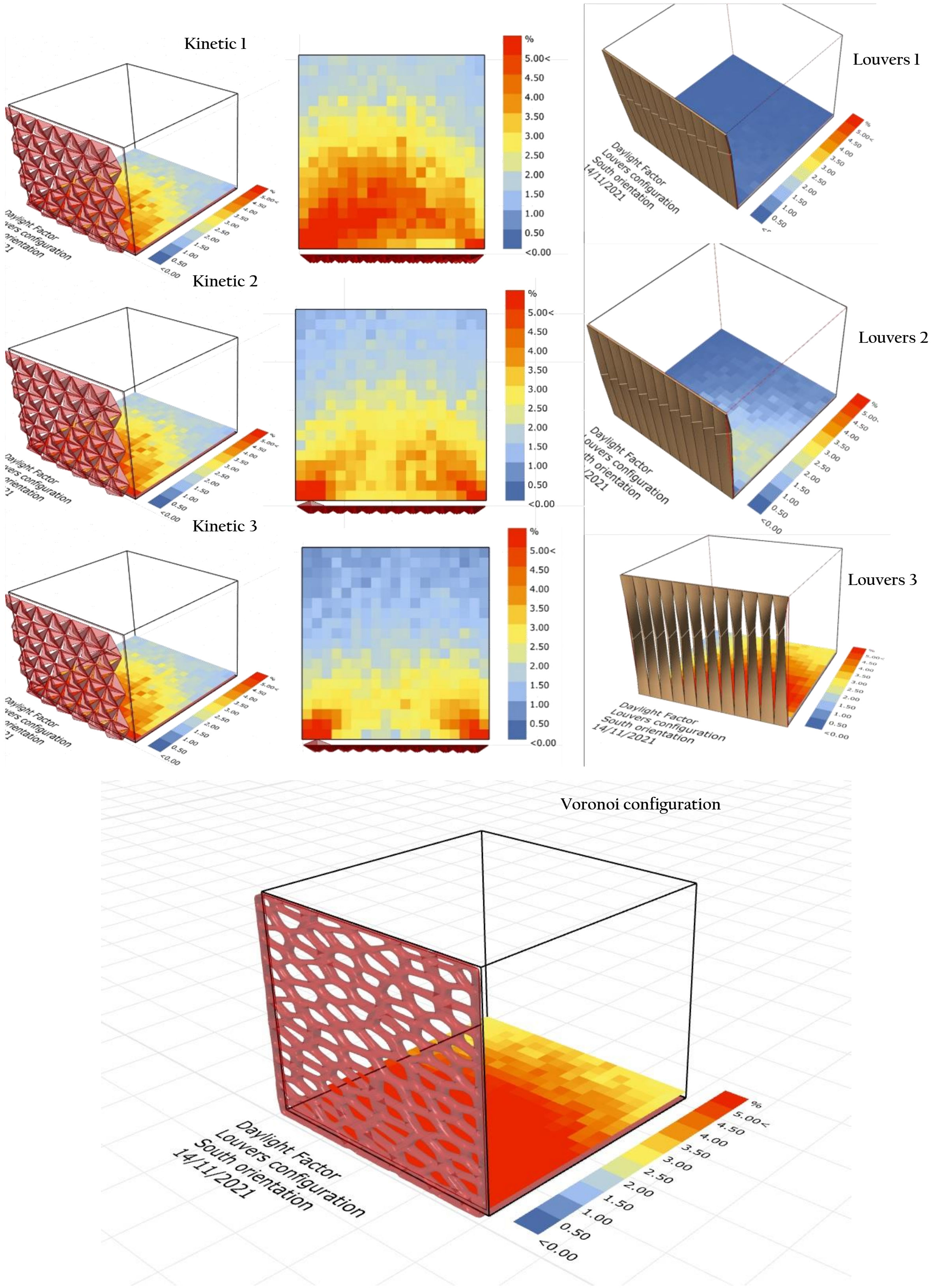

Figure 6.20: Daylight performance simulation of the optimized configurations (Daylight factor) (Source: Author, 2021)

6.3.1.5. Daylighting optimum solution

According to the Figure 6.21, which illustrates the distribution of spatial daylight autonomy and useful daylight illuminance within the patient room subsequent to the optimization process. This signifies a substantial enhancement in sDA (300 Lux/50%) and UDI (100–300 lux) within the room. The pinnacle of daylighting performance, as represented by the optimal solution, achieved the highest values within the selected set of optimal solutions—namely, an average sDA of 94.5% and UDI of 78.3%. In contrast to the base case, this notable augmentation in sDA and UDI levels can be attributed to the harmonious amalgamation of double glazing low-E and a shading device configuration, which resulted in a uniform and widespread distribution of values. The outcomes underscore an amplified distribution of daylight throughout the case study area, with approximately 80% of the patient room surface experiencing values ranging from 80% to 100% for UDI. This unequivocally points towards a significant enhancement in daylight levels within the room.

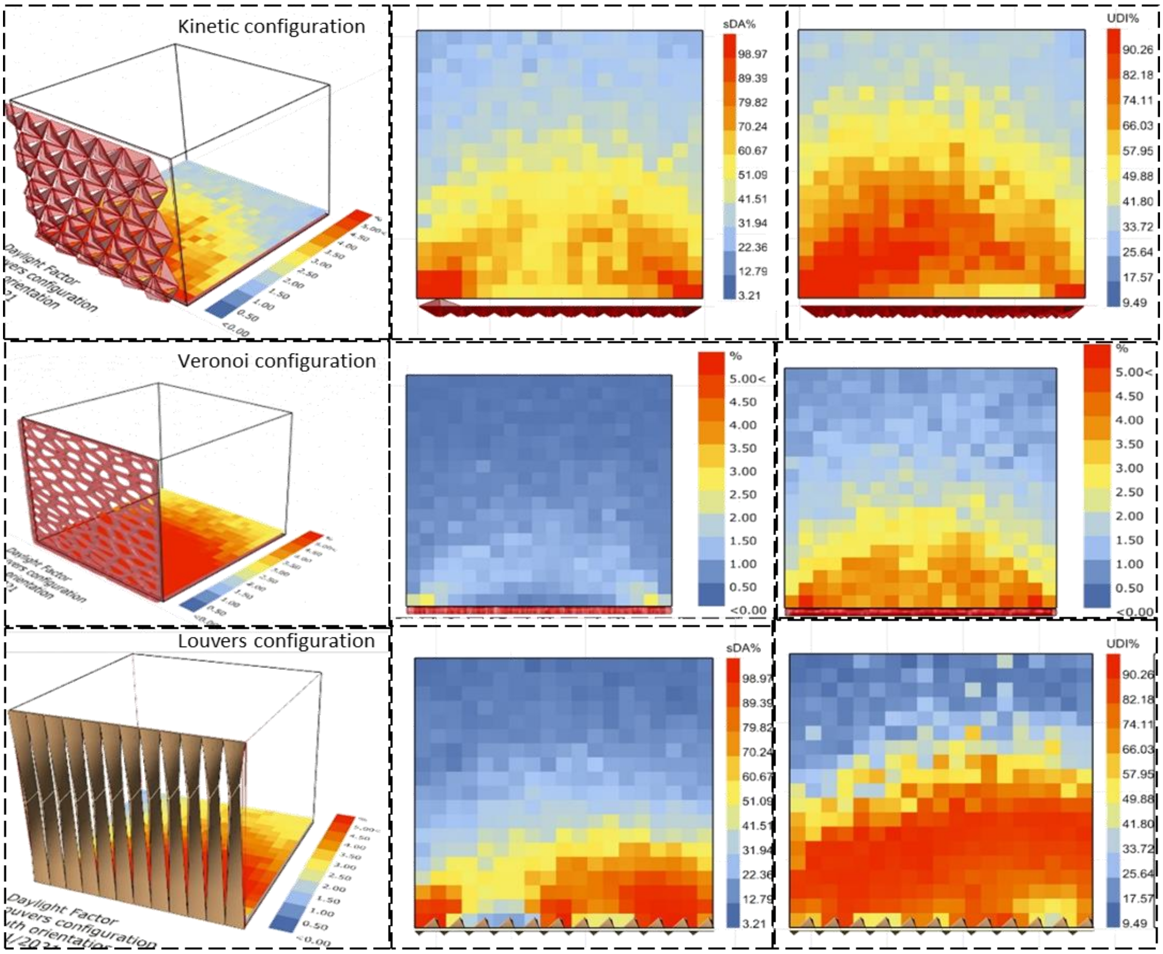

Figure 6.21: Daylight optimum solution simulation of Kinetic, Louvers and Voronoi configurations, Spatial Daylight Autonomy and Useful Daylight Illuminance (sDA, UDI) (Source: Author, 2021)

6.3.1.6. Energy optimum solution

As illustrated in Figure 6.22, the depiction of Energy Use Intensity (EUI) across the span of a year provides valuable insights into the energy consumption pattern. Notably, the highest levels of energy consumption manifest during the months of June, July, and August. This notable surge in energy demand during this period is a direct consequence of the elevated temperatures characterizing the hot and arid climate, necessitating extensive usage of cooling systems to maintain indoor comfort conditions. However, a striking transformation becomes evident when the optimization model is introduced for comparison against the base case model.

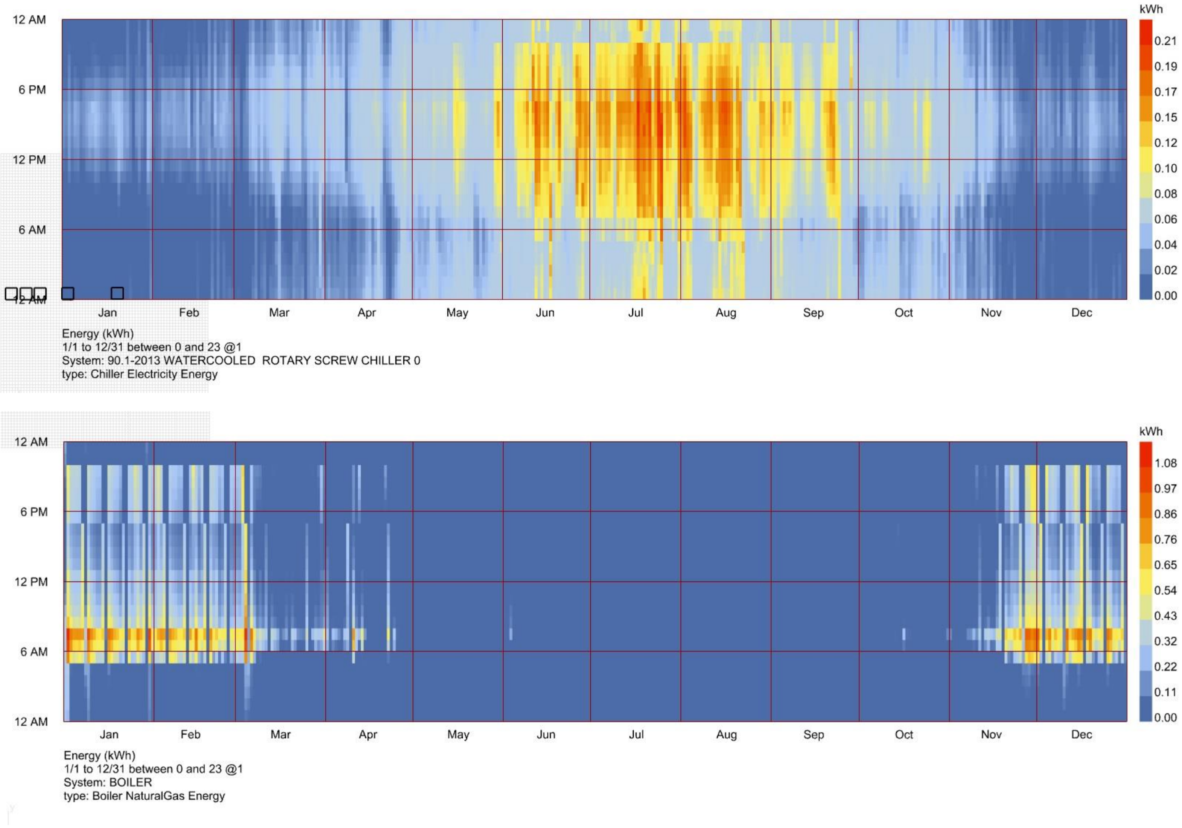

Figure 6.22: Annual EUI Energy Use Intensity consumption for cooling and heating of the optimum solution (Source: Author using Ladybug tool)

Within this analytical framework, the EUI exhibits a successful decline, marking a transition from an initial value of 158.1 Kwh/m²/year down to an impressively lowered value of 144.0 Kwh/m²/year. This transition equates to a substantial improvement of 14.1% in EUI efficiency. This noteworthy reduction in energy intensity is a testament to the prowess of the optimization model in mitigating the adverse effects of heightened energy demand during the peak summer months. By intelligently integrating design parameters, such as double glazing low-E and an optimized shading device configuration, the optimization process contributes to the alleviation of cooling system reliance, effectively curbing energy consumption. The resultant EUI improvement not only signifies heightened energy efficiency, thus potentially translating into reduced operational costs, but also underscores a conscientious step towards more sustainable and environmentally conscious building design. Consequently, this optimization-driven reduction in EUI encapsulates a meaningful stride towards harmonizing indoor comfort needs with energy conservation imperatives within the context of the demanding hot and arid climate.

6.3.2. The comparative Analysis findings with the base case results

In order to comprehensively grasp the comparison between the distributions of objective values in the base case model and those of the non-dominated solutions of the first configuration (kinetic design) (as showed in Table 6.2), a box plot was generated, as depicted in Figure 6.23. In the base case model, the sDA and UDI values (measured in percentage) remained consistent at 44.3 and 35.2, respectively. Conversely, the non-dominated solution set exhibited sDA and UDI outcomes spanning a broader range, from 68.0 to 94.3% for sDA with a median of 84.7%, and from 64.9 to 73.2% with a median of 69.9% for UDI. As for the EUI values (measured in Kwh/m²/year), the base case model retained a steady value of 158.1.

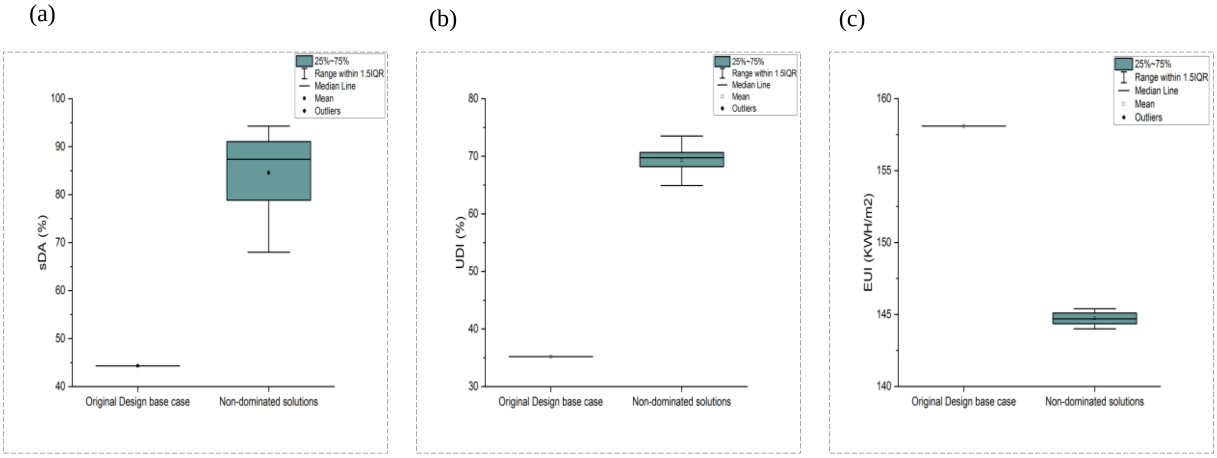

Figure 6.23: Box plot comparative Analysis of the original design (base case model) and Non-dominated solutions objectives': (a) Spatial Daylight Autonomy (sDA) values; (b) Useful Daylight Illuminance (UDI) values; (c) Energy Use Intensity (EUI) values for Kinetic configuration (Source: Author, 2021)

Comparatively, the non-dominated solution EUI values showcased even distribution, spanning from 144.0 to 145.4 Kwh/m²/year, with a median of 144.7 Kwh/m²/year. These results underscore the superior attainment of the non-dominated solutions in contrast to the original design, solidifying the effectiveness and reliability of the proposed approach. The evaluation of a representative patient room, fashioned based on the characteristics of the original model, highlighted limited daylight penetration throughout the day, thereby necessitating substantial reliance on artificial lighting. Consequently, hospitalized patients were deprived of the benefits of natural light.

In contrast, results gleaned from the optimization model indicated a discernible enhancement in the performance of the dynamic facade compared to the existing case study. This manifested in increased sDA and UDI values alongside reduced energy consumption. These findings illuminate the synergistic potential of the dynamic shading system, particularly when combined with efficient glazing and wall construction materials. Collectively, these elements serve to amplify indoor daylight availability within the context of a hot and arid region.

6.4. Conclusion

Through the exploration of analysis outcomes, this chapter last has effectively showcased the potential of employing parametric workflows and genetic algorithms optimization to engineer inventive facade designs for patient rooms, thereby substantially enhancing daylight performance at the initial stages of scheme development. In the pursuit of augmented daylight efficacy coupled with reduced energy consumption, this study harnessed a multi-objective optimization model using Grasshopper and Rhinoceros software. This approach enabled the identification of a diverse array of unconventional shading device designs, attaining a delicate equilibrium between maximizing daylight performance and minimizing energy expenditure. Comparing the outcomes of this optimization endeavor with those of the base case model, notable advancements were unveiled in the dynamic facade system's performance when contrasted with unshaded alternatives. This manifested as elevated Spatial Daylight Autonomy (sDA) and Useful Daylight Illuminance (UDI) values, coupled with a concurrent reduction in Energy Use Intensity (EUI), all while maintaining a pleasing glare-free, indoor daylight environment for patients. The genetic algorithms methodology adopted within this workflow exhibited a gradual progression in daylighting performance across the course of 15 Generations. The culmination of this optimization process yielded 50 non-dominated solutions, inclusive of the selected optimal solutions that align with the pre-established criteria.

This investigation underscores the efficacy of integrating parametric analysis with evolutionary algorithms as a dependable avenue for architects and designers to attain optimal solutions within the realm of building environmental performance challenges. It is crucial to acknowledge that this study, while promising, concentrated solely on optimizing a singular patient room within a specific case study context. To advance the applicability of optimization in the domain of building design, future research can potentially broaden its scope by encompassing a spectrum of criteria, encompassing thermal, energy, and visual comfort aspects.

Notwithstanding its limitations, this approach unveiled its potential to effectively respond to evolving design alternatives, offering facade design solutions that substantially elevate daylight performance. This proposition bears particular relevance in scenarios such as the patient room sample explored herein, where the physical environment profoundly influences patients' well-being and productivity. The imperative of prioritizing patient health within every facet of building design remains undeniably pertinent, a principle underscored by the promising outcomes of this study.

General conclusion

General conclusion

The primary objective of this dissertation is to support the creation of sustainable hospital designs appropriate for hot and arid conditions. This objective will be accomplished by employing a parametric workflow and utilizing genetic algorithms for building performance optimization to pinpoint the most advantageous indoor daylight conditions. The overarching aim of this doctoral research is to formulate a systematic approach to assess and enhance the efficiency of daylighting in patient rooms. Specifically, the main goal of this study is to devise a technique for refining the performance and depiction of architectural daylighting within patient rooms, employing genetic algorithms (GAs). This approach enables designers to thoroughly examine alternative building designs, precisely assess the daylight and energy efficiency of each design, and automatically discover design possibilities that offer optimal performance.

The results of this dissertation demonstrate that parametric workflow and genetic algorithms optimization can effectively generate innovative facade designs for patient rooms, enhancing daylight performance during the early stages of the design process. The initiation of this research involved three initial hypotheses, paving the way for the examination findings outlined in the ensuing key conclusions:

Initially, in a theoretical framework, we laid the groundwork for comprehending, examining, and suggesting alternatives through a range of theories and models. We emphasized the complex ideas encapsulated within the hypothesis, including daylight and energy efficiency in healthcare structures, parametric design, and optimization using genetic algorithms. As a result, we thoroughly investigated various studies from diverse angles and methodologies that address the application of genetic algorithms in the optimization of daylight and energy performance for buildings. In the preliminary phase encompassing the initial three chapters dedicated to tackling the research quandary, an in-depth examination of existing literature was undertaken to furnish perspectives and lay the groundwork for the qualitative approach. This review of literature had the objective of thoroughly surveying the current insights and grasp of the correlation between daylight and well-being. The extensive body of literature underscored the advantageous impact of daylight on patients' health and the energy efficiency of buildings. Nevertheless, prior optimization studies had not adequately addressed the concurrent optimization of both daylight performance and energy efficiency. This investigation seamlessly integrated the processes of daylighting and energy simulation, allowing for the evaluation of energy efficiency while taking into account the incorporation of daylight.

Secondly, the subsequent part of the research methodology encompassed the implementation of a quantitative strategy to delineate the case study and its surrounding circumstances, centering on the Hakim Saadan Hospital situated in Biskra city. Practical experiments related to daylight were carried out in March, June, and December of the year 2020. These experimental endeavors encompassed two pivotal facets: an empirical facet, entailing measurements conducted on-site within actual patient rooms, and the formulation of optimization algorithms reliant on simulations. The findings revealed that the South, East, and West patient rooms exhibited superior interior daylight performance during the morning, particularly in areas close to windows. However, in the afternoon, the average illuminance levels in the depth of the room during summer were below the recommended values, unlike winter when higher levels were observed due to the hot and arid climate. Additionally, the winter measurements indicated low daylight levels during occupied hours, leading to high artificial light consumption and a lack of daylight benefits for the patients. Consequently, the South and West facing patient rooms experienced excessive illuminance levels, causing visual discomfort and glare that could negatively impact patient health and create exhausting conditions.

Finally, to improve daylight performance while reducing energy consumption, a multi-objective optimization model was conducted using Grasshopper and Rhinoceros software. This model aimed to identify a wide range of unconventional shading device designs that maximize daylighting performance and minimize energy costs. By delving into the results of the analysis, the concluding section of this part has adeptly demonstrated the viability of utilizing parametric processes and optimizing genetic algorithms to craft innovative façade designs for patient rooms. This endeavor significantly amplifies the efficiency of daylight at the early phases of project formulation. Striving for heightened daylight efficiency along with diminished energy usage, this research leveraged a multi-faceted optimization model through the utilization of Grasshopper and Rhinoceros software. The results of the optimization process compared to the base case model revealed that a dynamic facade system improved conditions compared to options without shading systems. It demonstrated an increase in sDA and UDI metrics while minimizing EUI and ensuring a glare-free indoor daylight environment for patients. The genetic algorithms approach used in this workflow progressively enhanced daylighting performance over 15 generations, resulting in 50 non-dominated solutions that met the targeted criteria, including the selected optimal solutions. The integration of parametric analysis with evolutionary algorithms showcased its reliability in achieving optimal solutions for building environmental performance challenges faced by designers. However, it is important to acknowledge the limitations of this study, as it focused on optimizing a single patient room in a specific case study. Further improvements are required for the application of optimization in building design. Future research could explore a wider range of optimization criteria by combining thermal and energy indicators with visual comfort considerations. Despite these limitations, this approach demonstrates the potential to respond to various design alternatives and incorporate facade design solutions that significantly enhance daylight performance. This is particularly critical when addressing the patient room sample, where the physical environment has a substantial impact on patients' health and productivity. Therefore, prioritizing patient well-being should be a fundamental aspect of building design.

Recommendations

> "*A good environment with natural light and noise reduction reduces the risk of errors and benefits the health of the patients. This basic fact should inspire the design of hospitals when it comes to the architecture*"
>
> Carlo Volf, 2013

In accordance with the statement provided, scholarly research suggests that light plays a crucial role in matters of well-being. The thesis introduces an innovative approach that, drawing from these findings, illustrates how architectural designs can incorporate natural daylight more health-consciously. Drawing from the previously outlined findings and conclusions, the subsequent suggestions are put forth to ensure optimal indoor daylight conditions that cater to patients' visual well-being and create positive physiological settings. From this perspective, the study's results can assist in designing patient rooms in hospitals in hot and dry climates, taking into consideration the following recommendations:

- Prevent excessive glare, which leads to visual discomfort due to high luminance ratios and illuminance levels, by incorporating suitable sun-shading mechanisms within patient rooms. Combining indoor and outdoor sun-shading solutions in patient rooms will create an improved visual comfort environment, fostering more positive healing effects for the patients.
- The building's orientation is influenced by various factors. To begin with, the initial positioning of the building takes into account the uneven distribution of sunlight and

heat from the sun. Furthermore, central health considerations emphasize the significance of distributing morning and evening light appropriately. While morning light has beneficial effects, fostering the circadian rhythm and overall well-being, evening light and heat can disrupt the circadian rhythm and overall health. In addition, the architectural structure of the building can also be shaped based on the irregular distribution of sunlight across time and location. This can be achieved through different forms or protective elements that cause asymmetrical shading. In buildings with symmetrical forms, achieving this shading can involve asymmetric use of solar-protective glass, varying arrangements of light openings, or uneven physical shielding with respect to the cardinal directions (East, South, West, and North). Given that the specific latitude (34°5) experiences a hot and arid climate with exceedingly high summer temperatures, surpassing 40°C in July, it's advisable to orient patient rooms towards the North-East at a ratio of 30-40%. This orientation helps mitigate excessive illuminance levels, which, if not controlled, can lead to visual discomfort and glare, negatively affecting patient health and creating fatiguing conditions.

- The South orientation requires smaller window-to-wall ratios compared to other orientations due to the higher intensity of daylight. For a South-facing orientation, the optimal solution is double clear glazing with sun protection, using a window-to-wall ratio of 40% and the addition of special glazing enhances energy performance but diminishes daylighting performance.
- Incorporating suitable shading devices to openings in the hospital rooms for reducing the Energy Use Intensity (EUI) and increases the Useful Daylight Illuminance (UDI), it makes allowing for a window-to-wall ratio of 40% in East and West orientations.
- Given to the psychological effect of Daylight on patient well-being, indoor curtains and blinds should be adjustable according to the preferences of the individual, as an individual's discontent with their indoor daylight settings could lead to elevated stress levels.
- Furthermore, the amalgamation of multiple factors that could impact patients' physical and physiological well-being, such as thermal comfort, indoor air quality, and acoustic satisfaction, should also be taken into account to determine the extent of their influence on indoor environmental conditions.
- Hence, additional research is imperative and should be integrated into the planning of healthcare establishments to create an ideal setting that promotes patient well-being.

The outcomes of such investigations would hold immeasurable value for patients striving to restore their health.

- Concerning the utilization of the Genetic Algorithms (GAs) methodology, it has found extensive application in enhancing building performance across various sectors and disciplines. This investigation represents an incremental contribution that underscores its aptness for addressing architectural and healthcare building design challenges. Therefore, it is advisable to employ this approach to discover optimal daylight design solutions through a constrained series of simulations, not exclusively limited to healthcare facilities but also encompassing other building types. Nonetheless, additional research is warranted to evaluate alternative random optimization techniques, verifying its preeminence in addressing such design complexities.

The limits of research

Despite the promising nature of this work and its comprehensive coverage of all facets related to this matter, there remain constraints and deficiencies, spanning the realms of data collection, processing, and result interpretation. Numerous limitations were outlined at the inception of this research. Begin with the study's scope, while this investigation exclusively concentrated on the building facades as a pivotal architectural component, the identical methodology possesses the potential for expansion and application to alternative building elements or architectural categories.

- Although the ongoing advancements in the fields of computer science and artificial intelligence, the process of optimization remains intricate. Therefore, the approach in question demands a high level of expertise in various areas. This includes a strong grasp of computational design skills, substantial experience in energy modeling, and the ability to proficiently navigate multiple software programs. However, it is important to note that, at its current stage, this approach is not yet suitable for architects to effortlessly integrate into their design workflows.
- In this study, the employed optimization technique is the genetic algorithm. This algorithm operates by selecting individuals at random from the existing population and utilizing them as parent candidates for generating the offspring of the subsequent generation. Due to the inherent randomness in the selection procedure, it is typical for each optimization run to yield diverse design alternatives with varying levels of performance. Among these, the optimal design derived from each optimization

iteration represents one of the finest choices attainable. In fact, it's important to recognize that identifying a globally optimal design is unfeasible due to the inherent complexities of the optimization landscape.

- The procedure established within this workflow exclusively addresses the impact of the hospital room's geometric variables, omitting the consideration of other factors like vegetation and materials that could also play a role.
- The constraints encompass the fact that this research solely focused on optimizing a solitary patient room within a specific case study. There remains room for enhancement in the potential applications of optimization within buildings. Subsequent investigations have the opportunity to explore a wider array of optimization criteria by integrating thermal and energy metrics with visual comfort parameters.
- The methodology strongly depends on the computational capacity available. Optimization times for each workflow range depending on the processing speed of the computer's central unit, despite the straightforward geometry of the case study model. Furthermore, this optimization procedure engages multiple software applications. If confronted with a complex design model, the data transfer between these applications might become disrupted, potentially leading to the cessation of the optimization process. Hence, to effectively address more intricate design challenges, additional technical assistance becomes imperative.

Research Insights

The future perspectives outlined below represent novel avenues for upcoming research endeavors. These areas warrant heightened focus and will significantly enhance the scope of sustainable development and the constructed environment. The advancement of this knowledge has the potential to make substantial contributions to the enduring sustainable progress of our urban areas.

- In the forthcoming era, architecture will encompass more than just energy considerations, construction expenses, and operational costs; it will also encompass health and the benefits derived from well-being.
- Additional effort is required to extend the scope of optimization goals, encompassing factors such as cost, thermal comfort, visual satisfaction, energy generation, and overall building life cycle performance. Moreover, there is a necessity for multi-objective optimization techniques to assess multiple performance criteria concurrently.

- Prospective endeavors also involve implementing this optimization procedure in practical architectural design ventures. These could encompass projects within architectural design firms or even student design assignments with the combination of multiple parameters.
- Finally, executing this framework within diverse building design contexts while adhering to multi-objective optimization principles. Focusing on performance priorities and their harmonization with the subjective preferences of designers, this methodology has the potential for further enhancement.

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Appendices

APPENDICES

Appendix A: Meteorological data of the city of Biskra

The "Grasshopper" software was used to illustrate the graphs of meteorological data for the city of Biskra using an "epw" format climate file over 15 years (2004-2018) was obtained from the Climate One Building website hourly weather data files.

The city of Biskra reaches high levels of temperatures due to intense solar radiation. Figure A.1 displays the yearly hourly outdoor temperature patterns. Throughout the cold season, spanning from December to February, daytime temperatures remain mild, ranging from 10°C to 25°C, while nighttime temperatures become chilly, dropping below 5°C. Biskra also undergoes a prolonged hot period from May to October, during which the temperature can surpass 40°C in summer.

Figure A.1 also demonstrates the prevailing low relative humidity in this region, particularly during the day and notably in the summer months, where it descends to less than 19%. In winter, relative humidity fluctuates between 46% and 55% during the day and rises to 80% at night.

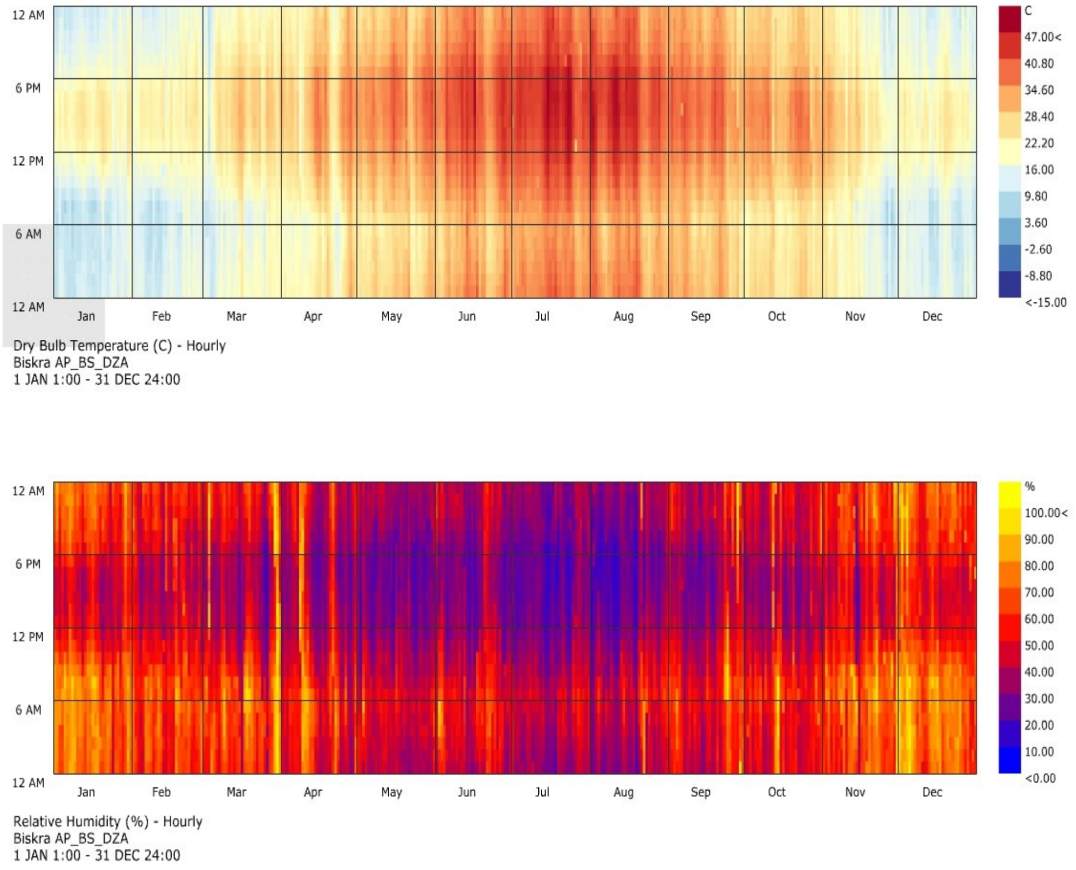


Figure A.1: Dry bulb temperature and Relative Humidity of Biskra city in Algeria (Source: Author, 2021)

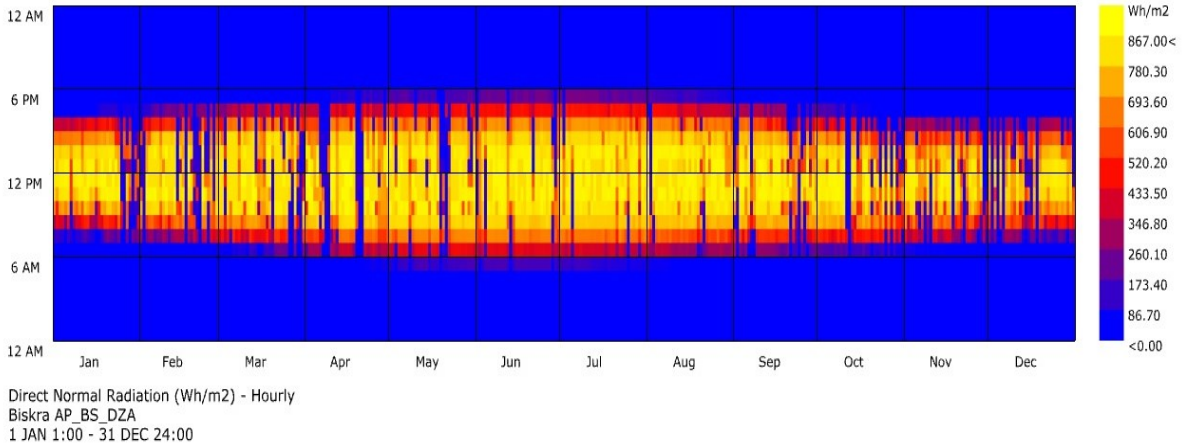
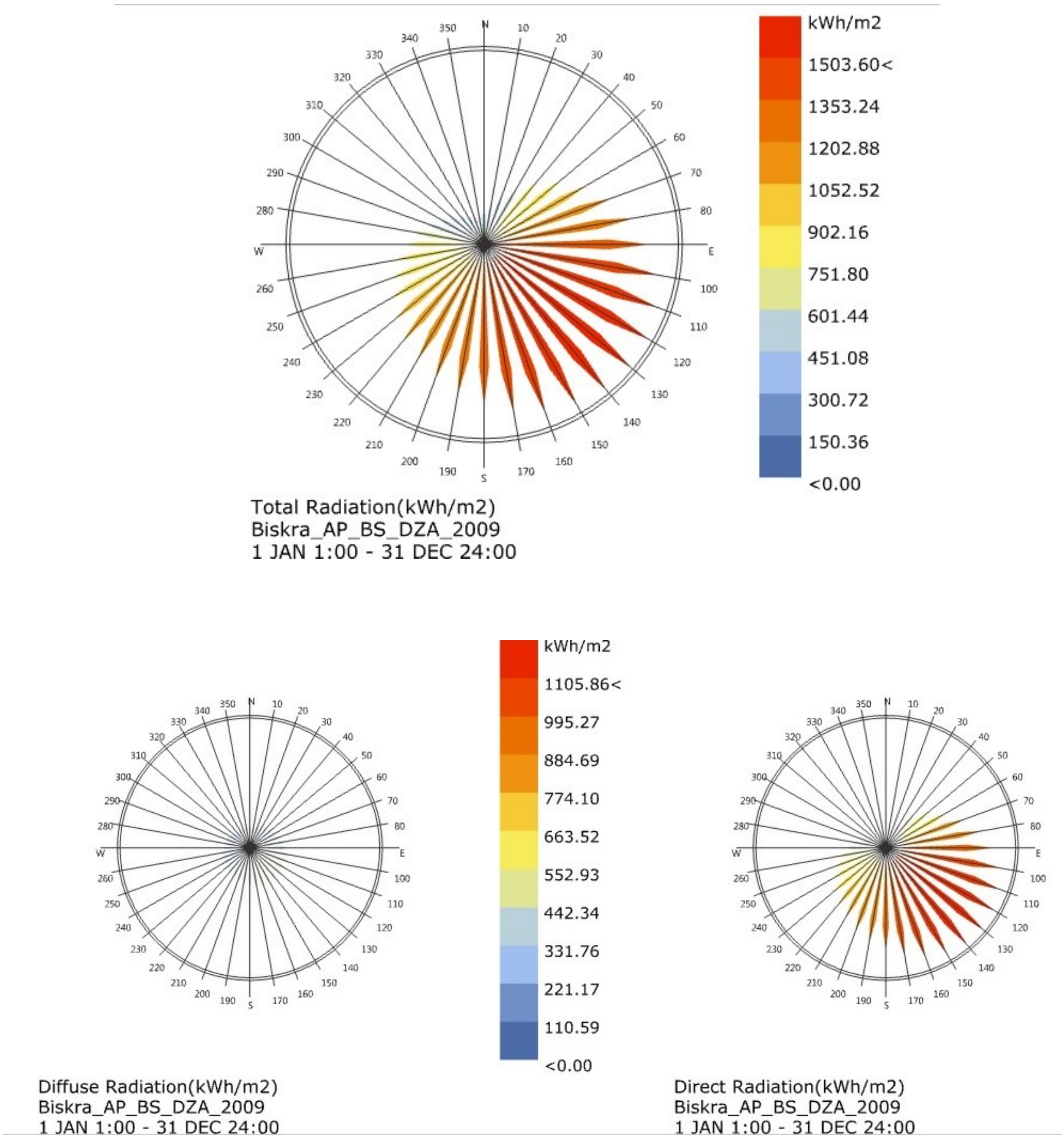


Figure A.2: Direct and Diffuse normal Radiation (KWh/m2) of Biskra city in Algeria (Source: Author, 2021)



Total Radiation(kWh/m2)
Biskra_AP_BS_DZA_2009
1 JAN 1:00 - 31 DEC 24:00

Diffuse Radiation(kWh/m2)
Biskra_AP_BS_DZA_2009
1 JAN 1:00 - 31 DEC 24:00

Direct Radiation(kWh/m2)
Biskra_AP_BS_DZA_2009
1 JAN 1:00 - 31 DEC 24:00

Figure A.3: Direct and Diffuse normal Radiation (KWh/m2) of Biskra city in Algeria (Source: Author, 2021)

The climate of the city of Biskra is similar to that of desert regions due to its location in the northern part of the Grand Sahara. A clear sky prevails almost year-round, with luminance exceeding 100,000 lux, especially during the summer equinox (Figure A.2 and Figure A.3). The brightness reaches its peak at noon, and cloudless skies are dominant. Radiation values are very high throughout the year, especially during summer. This season was characterized by high values of direct and diffuse radiation with a global radiation of nearly 250 KWh/m² during the month of July. The longest sunshine duration in this city is around 12 hours during the month of July (Figure A.4).

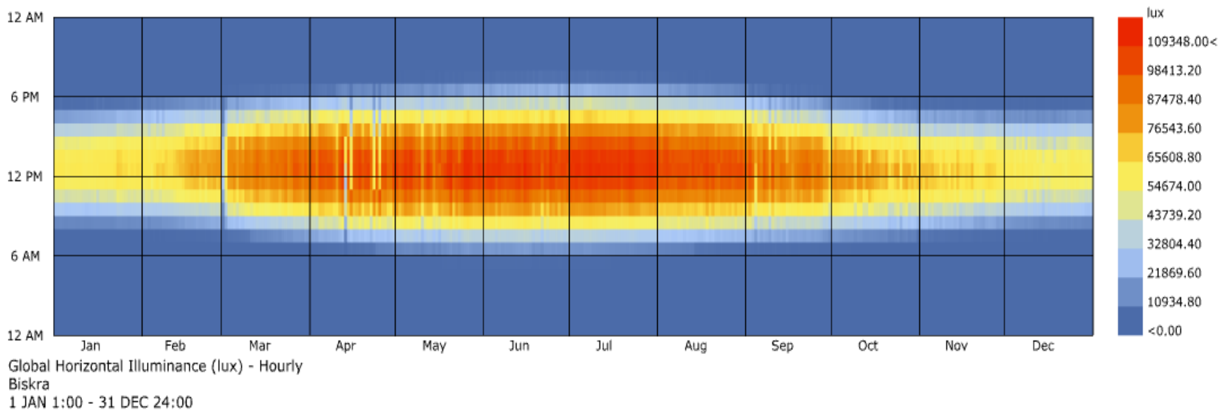


Figure A.4: Annual hourly overall horizontal illuminance of the city of Biskra (Source: Author, 2021)

In Biskra, rainfall is low and erratic as shown in Figure A.5. Annual precipitation in the city of Biskra is very low, characterized by scarcity and irregularity. The maximum amount of precipitation (20 mm) occurs in the month of March. During the winter season, there are an average of two to three days with precipitation, and the average rainfall is around 12 mm. In contrast, the average precipitation during the summer period is almost negligible, reaching only 3 mm (Bergout, 2012).

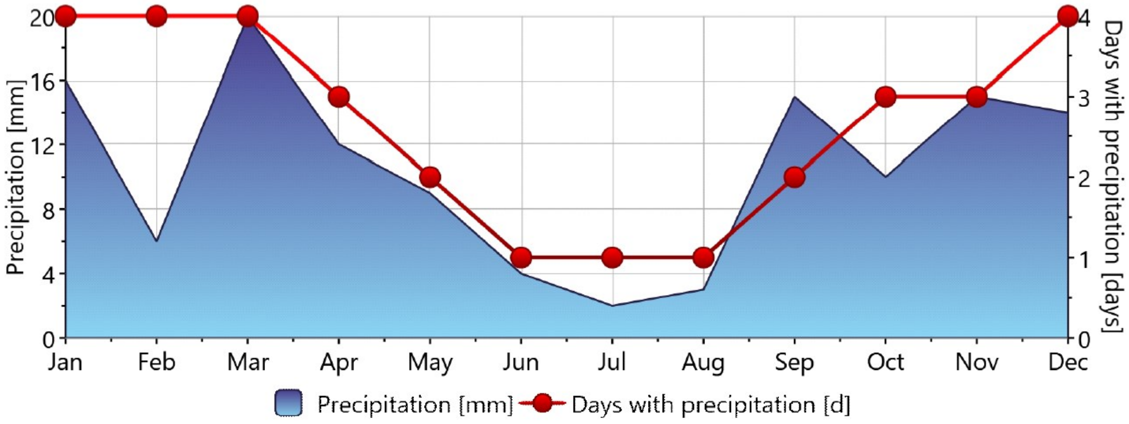
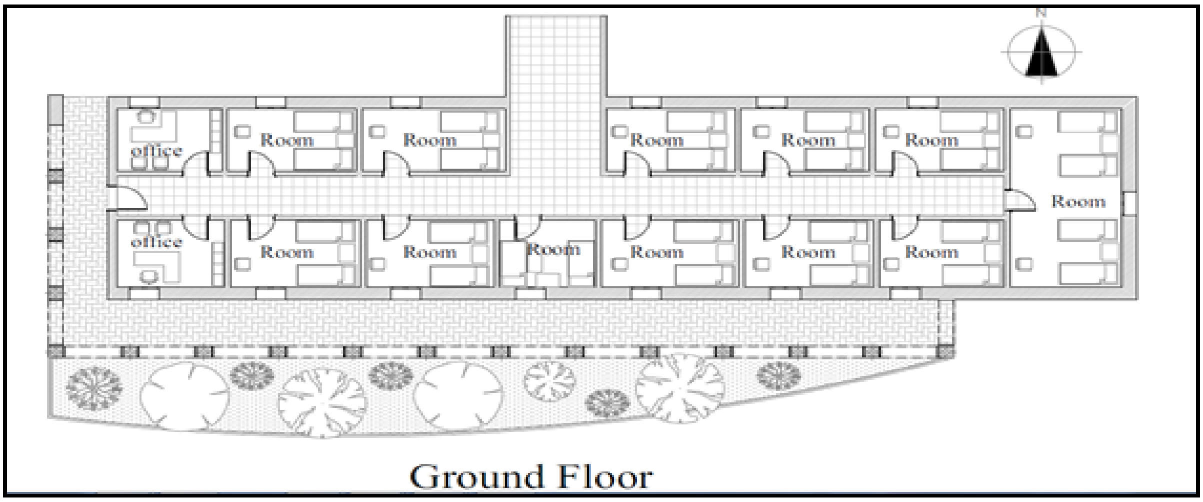


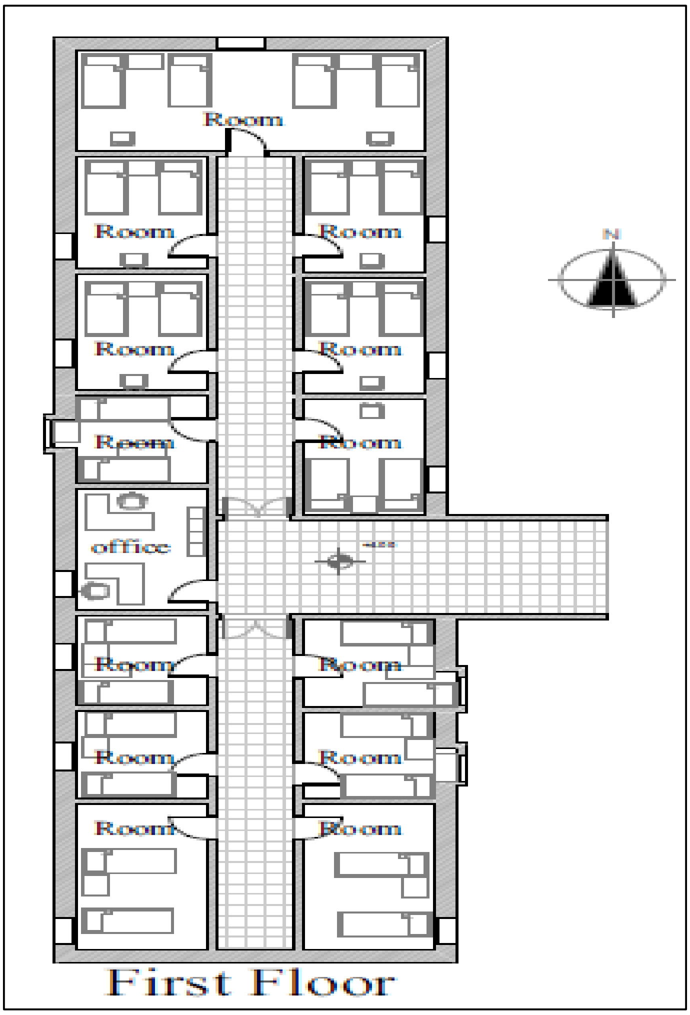
Figure A.5: Rainfall in the city of Biskra (Source: Meteonorm V.7.2)

Precipitation values are very low and do not exceed 20 mm.

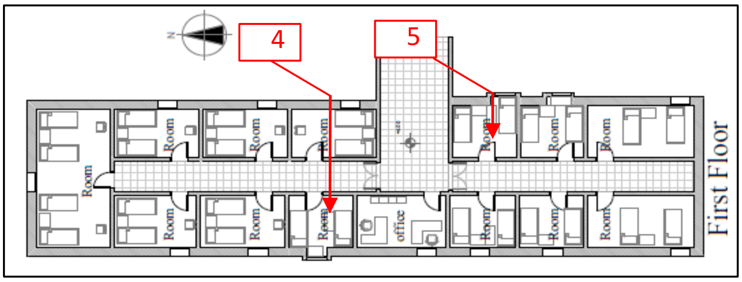
Appendix B: Floor plans of pediatric ward in Hakim Sadaane Hospital

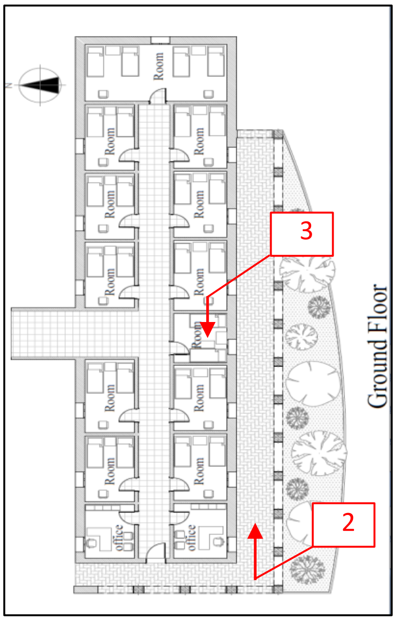


Ground floor Plan. ECH 1/200

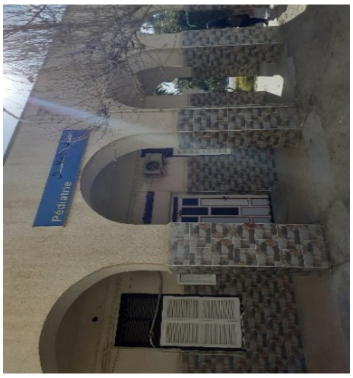


First floor Plan. ECH 1/200





(c)



(b)

(a)

Exterior views of patient

(d)

Appendix C: The following Tables C.1, C.2 and C.3 present the results of individual measurements of indoor illuminance levels.

Average illuminance (Lux) : clear sky **June (Summer)**

Room	Room 01 South			Room 02 West			Room 03 East		
points / Time	9 :00 Am	12 :00 Pm	16 :00 Pm	9 :00 Am	12 :00 Pm	16:00 Pm	9 :00 Am	12 :00 Pm	16:00 Pm
Point 1	790	1061	612	201	524	502	665	250	230
Point 2	524	871	601	442	2254	1718	1250	296	275
Point 3	325	450	296	213	1011	501	620	245	245
Point 4	1124	3250	1036	285	602	875	724	425	293
Point 5	624	1520	825	412	995	1521	2524	562	402
Point 6	324	525	378	400	832	850	1524	387	285
Point 7	825	956	856	223	380	563	510	400	234
Point 8	424	870	650	273	495	952	2785	1250	625
Point 9	210	451	325	205	398	514	1096	624	233

Average illuminance (Lux) : clear sky **December (Winter)**

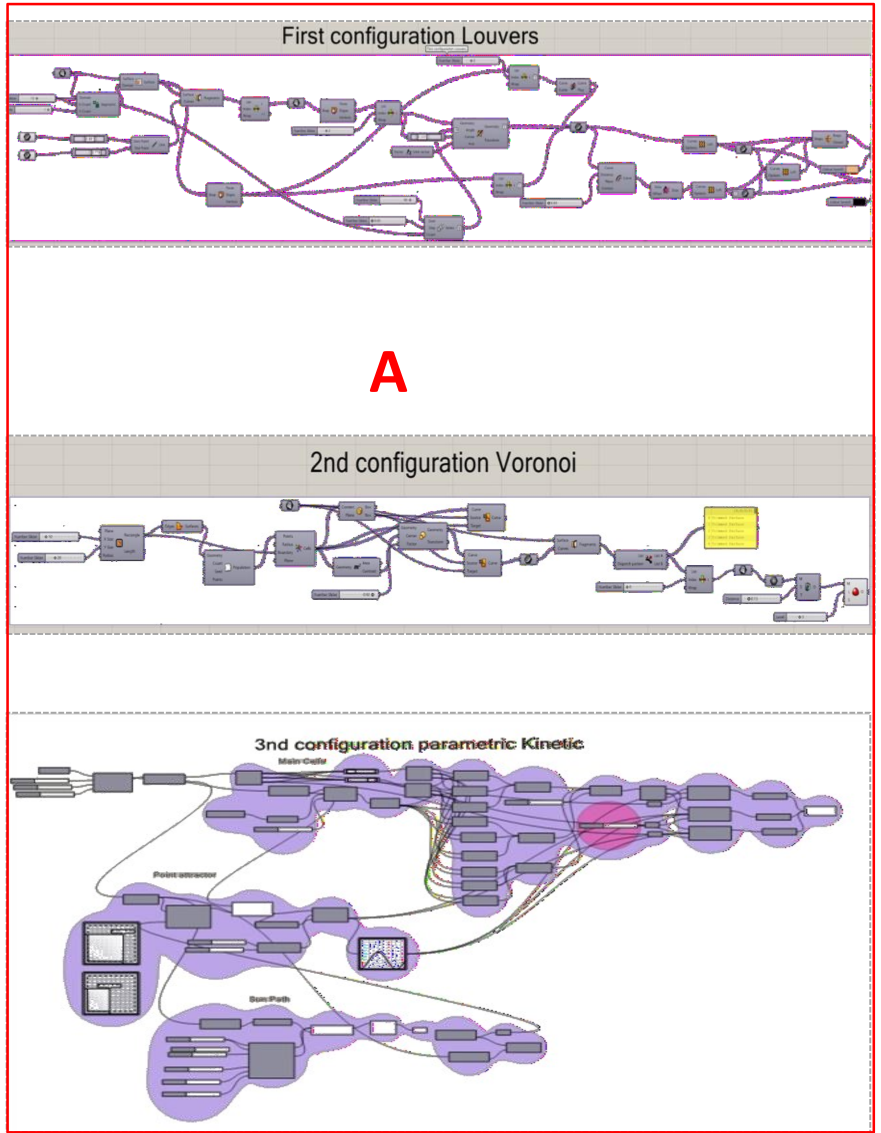
Room	Room 01 South			Room 02 West			Room 03 East		
points / Time	9 :00 Am	12 :00 Pm	16 :00 Pm	9 :00 Am	12 :00 Pm	16:00 Pm	9 :00 Am	12 :00 Pm	16:00 Pm
Point 1	465	628	96	325	285	120	208	265	63
Point 2	654	915	102	524	910	205	270	345	74
Point 3	210	820	38	312	852	145	293	365	62
Point 4	1260	1525	466	295	375	135	296	456	105
Point 5	635	1250	202	403	645	196	585	625	175
Point 6	245	903	75	395	746	152	456	602	107
Point 7	312	624	109	157	267	76	296	479	106
Point 8	302	910	130	256	380	95	985	710	390
Point 9	195	798	71	162	368	86	465	702	112

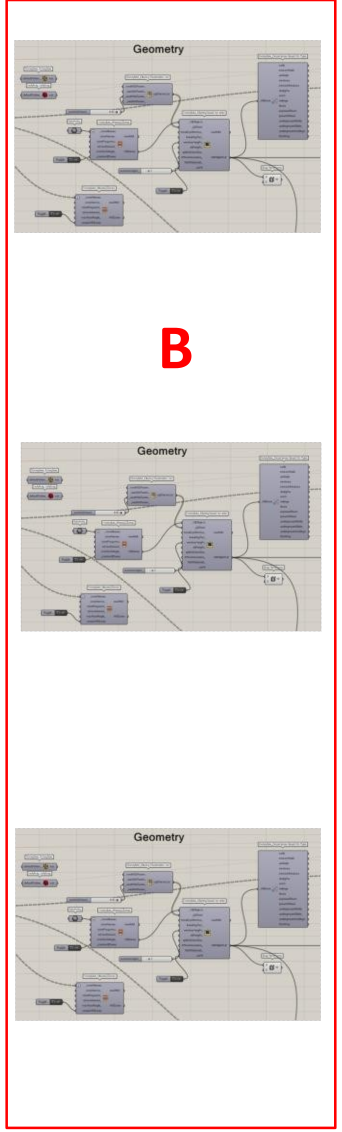
Average illuminance (Lux) : clear sky

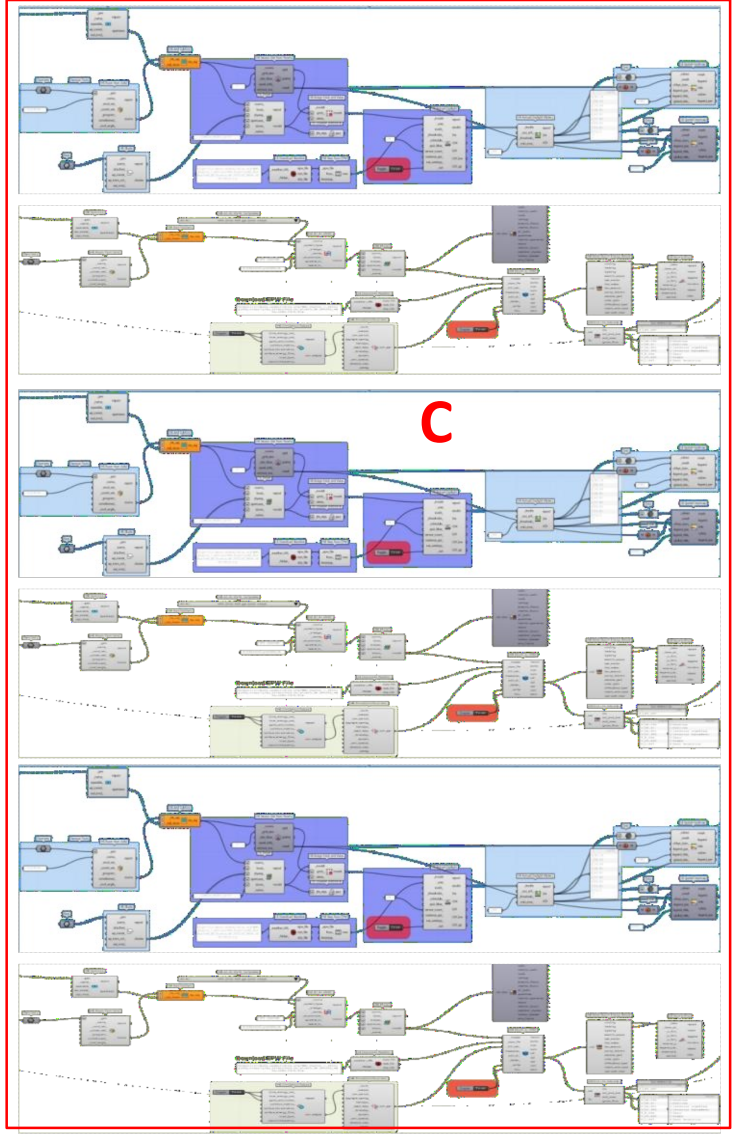
March (Spring)

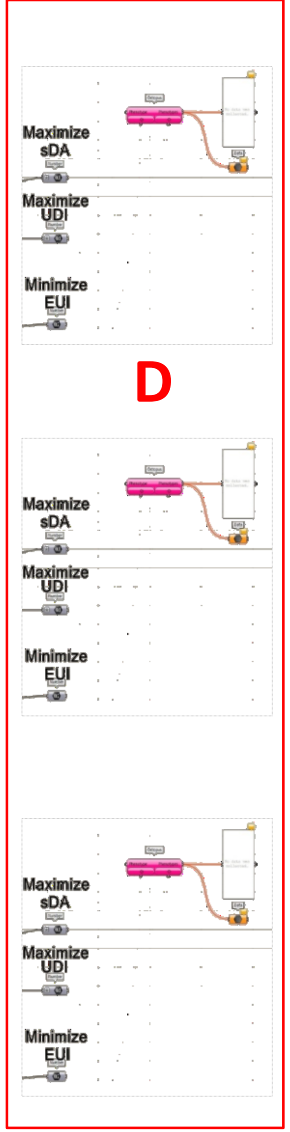
Room	Room 01 South			Room 02 West			Room 03 East		
points / Time	9 :00 Am	12 :00 Pm	16 :00 Pm	9 :00 Am	12 :00 Pm	16:00 Pm	9 :00 Am	12 :00 Pm	16:00 Pm
Point 1	1002	634	364	183	175	328	423	275	195
Point 2	1201	1245	395	803	625	998	925	351	198
Point 3	601	701	214	215	601	448	912	365	156
Point 4	2100	3540	1680	445	257	501	542	452	241
Point 5	942	2549	812	623	502	985	1235	520	350
Point 6	497	856	315	446	498	815	1205	660	230
Point 7	380	509	902	232	310	344	632	921	158
Point 8	465	947	617	255	289	528	2510	1695	542
Point 9	379	614	321	201	250	689	2120	1386	201

Appendix D:

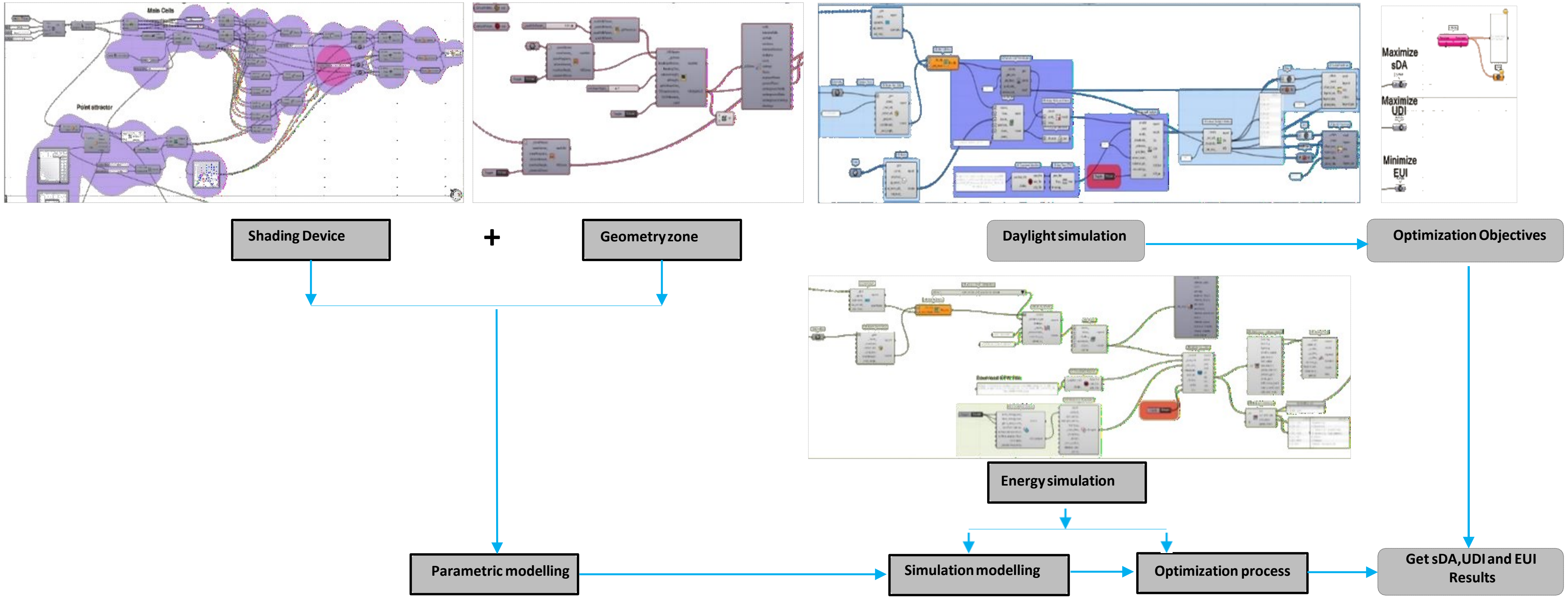

First configuration Louvers
A
2nd configuration Voronoi
3nd configuration parametric Kinetic
Main Cells
Point attractor
Sun Path


Geometry
B
Geometry
Geometry

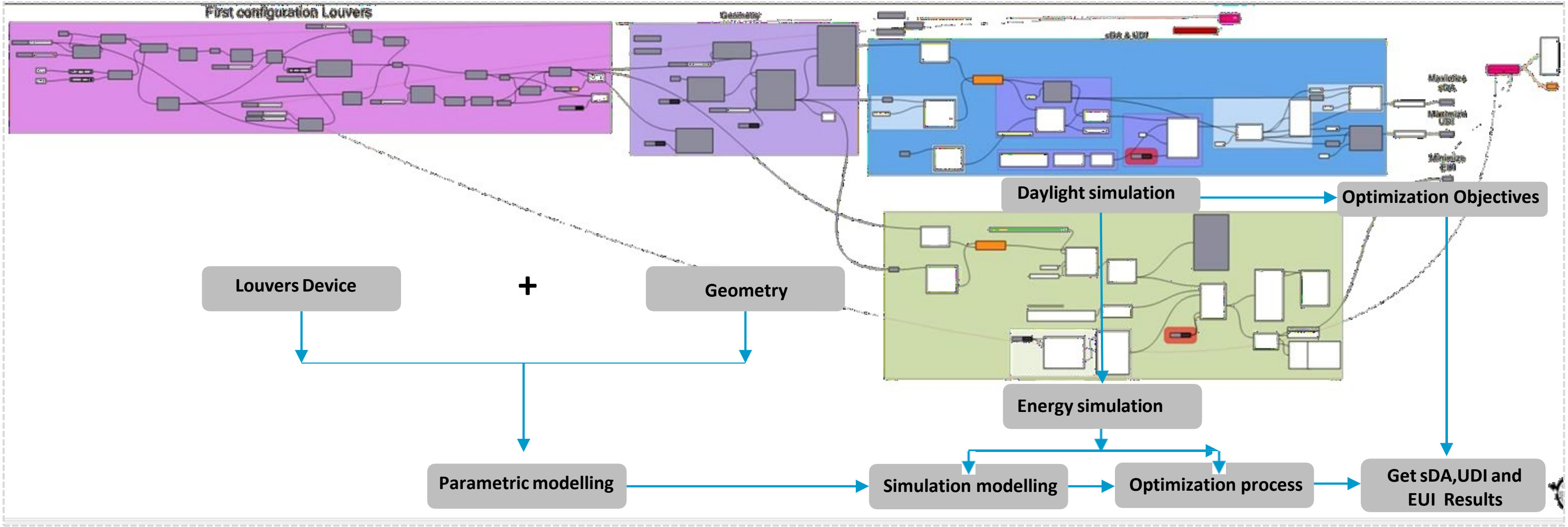

C


Maximize sDA
Maximize UDI
Minimize EUI
D
Maximize sDA
Maximize UDI
Minimize EUI
Maximize sDA
Maximize UDI
Minimize EUI

Appendix E:


Main Cells
Point attractor
Maximize sDA
Maximize UDI
Minimize EUI
Shading Device
+
Geometry zone
Daylight simulation
Optimization Objectives
Energy simulation
Parametric modelling
Simulation modelling
Optimization process
Get sDA,UDI and EUI Results

Appendix E:


First configuration Louvers
Geometry
sDA & UDI
Maximize sDA
Maximize UDI
Minimize EUI
Daylight simulation
Optimization Objectives
Louvers Device
+
Geometry
Energy simulation
Parametric modelling
Simulation modelling
Optimization process
Get sDA,UDI and EUI Results

Appendix F:

Solutions	Y	sDA %	UDI %	EUI KWH/m2	Wall construction	Glass material	Shading Width Variations	Shading Count	Shading Angle
Solution1	90.8	94.3	64.9	144.3	Double brick with air cavity	Double glazed low-E (vacuum)	0.20	12	- 45°
Solution2	87.8	94.3	64.9	144.4	Double brick with air cavity	Double glazed low-E (vacuum)	0.20	11	- 45°
Solution3	94.2	91.0	68.2	144.7	Double brick with air cavity	Double glazed low-E (vacuum)	0.19	12	- 45°
Solution4	94.5	91.1	68.2	144.7	Double brick with air cavity	Double glazed low-E (vacuum)	0.19	12	- 45°
Solution5	92.6	90.0	68.3	144.6	Double brick with air cavity	Double glazed low-E (vacuum)	0.19	12	- 30°
Solution6	99.5	84.7	69.6	144.0	Double brick with air cavity	Double glazed low-E (vacuum)	0.16	11	- 30°
Solution7	99.6	83.7	69.9	144.1	Double brick with air cavity	Double glazed low-E (vacuum)	0.15	12	- 30°
Solution8	97.6	90.6	70.5	145.1	Double brick with air cavity	Double glazed low-E (vacuum)	0.18	12	- 30°
Solution9	69.4	81.4	69.9	145.1	Double brick with air cavity	Double glazed low-E (vacuum)	0.16	12	- 30°
Solution10	62.8	76.3	70.8	145.1	Double brick with air cavity	Double glazed low-E (vacuum)	0.14	12	- 25°
Solution11	50.6	69.3	72.9	145.4	Double brick with air cavity	Double glazed low-E (vacuum)	0.12	11	- 15°
Solution12	51.5	68.0	73.5	145.4	Double brick with air cavity	Double glazed low-E (vacuum)	0.10	12	- 15°