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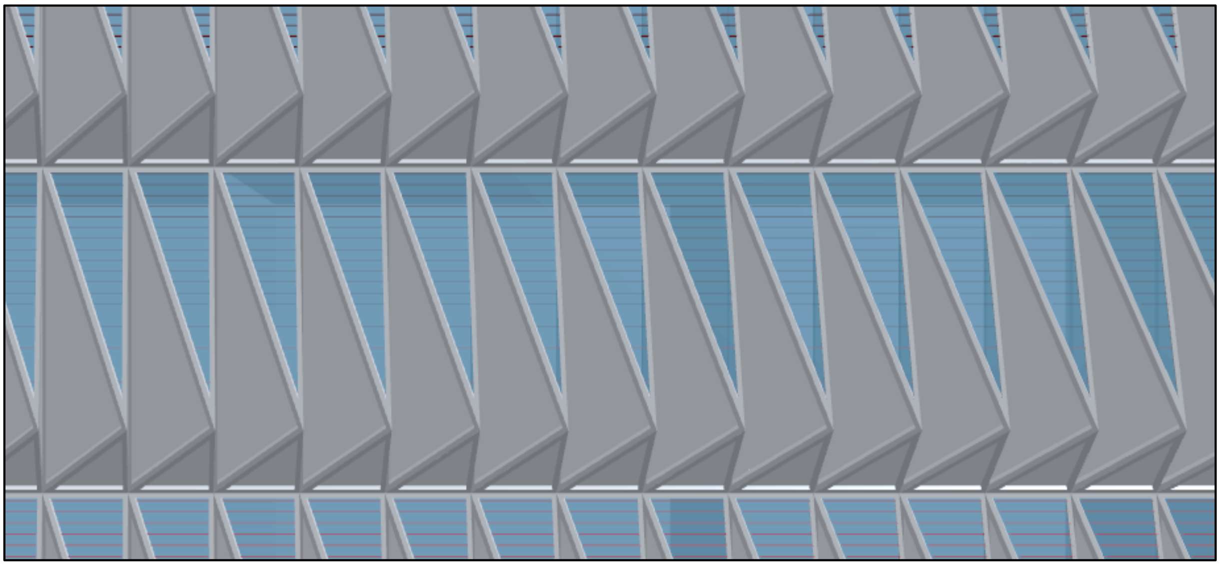

Dissertation

A Computational Framework for the Optimization of the Environmental Performance of Facades in Early Design Stages

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TECHNISCHE UNIVERSITÄT MÜNCHEN

Fakultät Architektur

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Abstract

In this thesis a simplified framework and design decision support tool was developed to aid designers and architects in the domain of multidimensional optimization of building facades, where environmental performance measures are enhanced by incrementally improving the façades design using multi-objective optimizations. The framework facilitates the generation of architectural forms of building envelopes according to different performance aspects such as daylighting, energy efficiency, thermal comfort, visual comfort, energy generation, and life cycle analysis. It utilizes the flexibility of parametric design and scripting interfaces as front-end input tools (e.g. Python and Grasshopper for Rhinoceros 3D) and simulation software as building performance assessment tools (e.g. Energy Plus, Radiance, and Daysim). The multi-objective optimization problem can then be solved using evolutionary search techniques such as Pareto Genetic Algorithms. A visualization dashboard is developed to facilitate the visualization and analysis of optimization and simulations results. Case studies were used to demonstrate the framework's potential and its usability.. The thesis aims to show that this approach is specifically practical for contemporary design practices, as it offers the designers with a decision support tool that is based on a robust method for optimizing performative and constructible free-form architecture.

Keywords: Performance-Based Design; Parametric Modeling; Multi-Objective Optimization; Building Performance Simulation; Data Visualization; Energy Efficiency; Daylighting; Thermal Comfort; Visual Comfort

Zusammenfassung

Im Rahmen dieser Dissertation wird ein vereinfachtes Entwurfswerkzeug entwickelt, das Designer und Architekten bei der mehrdimensionalen Optimierung von Gebäudefassaden unterstützt. Mit diesem Designwerkzeug werden Maßnahmen bezüglich der Minimierung von Umweltwirkungen von Gebäuden, durch eine schrittweise Verbesserung der Fassadengestaltung, mit Hilfe mehrdimensionaler Optimierungen verbessert. Das Designwerkzeug bewertet die Leistung der Gebäudehülle nach verschiedenen Leistungsaspekten wie Tageslicht, Energieeffizienz, thermischer Komfort, Sehkomfort, Energieerzeugung und Lebenszyklusanalyse. Es nutzt die Flexibilität parametrischer Design- und Skriptschnittstellen als Front-End-Eingabewerkzeuge (z.B. Python und Grasshopper für Rhinoceros 3D) und dynamische numerische Simulationssoftware als Werkzeuge zur Bewertung der Gebäudeleistung (z.B. Energy Plus, Radiance und Daysim). Das mehrdimensionale Optimierungsproblem kann weiterführend mit Hilfe evolutionärer Suchstrategien, wie z.B. Pareto-genetischer Algorithmen, gelöst werden. Um die Analyse und Visualisierung von Optimierungs- und Simulationsergebnissen zu erleichtern, wird ein Visualisierungs-Dashboard entwickelt. Anhand von Fallstudien wurde das Erreichen der genannten Ziele nachgewiesen. Die Dissertation zeigt, dass dieser Ansatz speziell für zeitgenössische Designpraktiken praktikabel ist, da diese den Designern ein Werkzeug für Entscheidungshilfen bietet, das auf einer robusten Methode zur Optimierung der Leistungsfähigkeit von Gebäudefassaden basiert.

Schlüsselwörter: Parametrische Modellierung; mehrdimensionale Optimierung; Gebäudeleistungssimulation; Datenvisualisierung; Energieeffizienz; Tageslicht; Thermischer Komfort; Visueller Komfort

Abbreviations

2D	Two Dimensional
3D	Three Dimensional
AC	Alternating Current
ADPE	Abiotic Resource Depletion Potential for Elements
AGP	Annual Glare Percentage
AP	Acidification Potential
ASE	Annual Sunlight Exposure
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
BIM	Building Information Modeling
BIPV	Building-Integrated Photovoltaics
BPS	Building Performance Simulation
BREEAM	Building Research Establishment Environmental Assessment Method
CAD	Computer-Aided Design
CBDM	Climate Based Daylight Metrics
CGI	CIE Glare Index
CIE	The International Commission on Illumination (Commission Internationale de l´Eclairage)
CSV	Comma-Separated Values
DA	Daylight Autonomy
DAcon	Continuous Daylight Autonomy
Dav	Daylight Availability
DC	Direct Current
DDPM	Dynamic Daylight Performance Metrics
DDS	Design Decision Support
DF	Daylight Factor
DGI	Daylight Glare Index
DGNB	German Sustainable Building Council (Deutsche Gesellschaft für Nachhaltiges Bauen)
DGP	Daylight Glare Probability
DIN	German Institute for Standardization (Deutsches Institut für Normung)
DRSM	Design Research Science Methodology
EP	Eutrophication Potential
EPBD	The Energy Performance of Buildings Directive

Abbreviations (cont.)

EUI	Energy Use Intensity
GA	Genetic Algorithm
GHG	Greenhouse Gases
GUI	Graphical User Interface
GWP	Global Warming Potential (For a time horizon of 100 years)
HAS	Horizontal Shading Angle
HVAC	Heating, Ventilation, and Air Conditioning
IES	Illuminating Engineering Society
IPAD	Integrative Performance Assessment Dashboard
IPO	Integrative Performance Optimization
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LEED	Leadership in Energy and Environmental Design
MRT	Mean Radiant Temperature
NZEB	Net Zero Energy Building
ODP	Ozone Layer Depletion Potential
PDH	Percentage of Discomfort Hours
PENRT	Total Non-renewable Primary Energy
PERT	Total Renewable Primary Energy
PMV	Predicted Mean Vote
POCP	Photochemical Ozone Creation Potential
PPD	Percentage of People Dissatisfied
PV	Photovoltaics
ROI	Return on Investment
sDA	Spatial Daylight Autonomy
SPEA	Strength Pareto Evolutionary Algorithm
SPT	Single Point in Time
UDI	Useful Daylight Illuminance
UGR	CIE Unified Glare Rating
VPL	Visual Programming Language
VSA	Vertical Shading Angle
WWR	Window-to-Wall Ratio

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Chapter 1: Introduction

1.1 Research background and motivation

Nowadays, the combined crisis of energy sources depletion and significant climate change generates a sense of urgency and demands fundamental changes in the way we are living. The atmosphere and ocean's temperatures have risen and greenhouse gases (GHG) emissions have reached unprecedented rates (Stocker et al. 2014). Climate change is the biggest challenge facing humanity nowadays. As a global threat that can be only solved with the cooperation of all nations, a global agreement on climate change was signed in December 2015 in Paris with an attempt to limit changes in global temperatures to below 2 °C or 1.5 °C warming in 2100 compared to pre-industrial levels. To achieve that, a significant reduction in CO_2 emissions has to be made (UNFCCC 2015).

The building and construction sector has a direct connection to the climate change phenomena. As a major source of CO_2 emissions and energy consumption, the building and construction sector accounts for nearly 40% of CO_2 emissions and energy consumption in developed countries surpassing other major sectors such as the industrial and transportation sectors (Pérez-Lombard et al. 2008). The effects of the building sector on the environment was highlighted in several reports from the United Nations Environment Programme (UNEP) where it was also noted that the building sector has the highest potential for delivering significant and cost-effective greenhouse gases emission reductions. Moreover, the global emission reduction targets cannot be met without supporting energy efficiency gains in the building sector (UNEP Sustainable Buildings & Construction Initiative 2009).

Architects and designers usually face these challenges while designing new buildings. In Europe, the 2010 Energy Performance of Buildings Directive made it mandatory that all new buildings must be nearly net-zero energy buildings by 31 December 2020 (European Parliament, Council of the European Union 2010). Several building codes worldwide and rating systems are now targeting more energy efficient designs and aiming to reach not only Net Zero Energy Buildings (NZEBs), but even buildings with a positive impact such as Plus Energy Buildings. Building facades and envelopes have a particularly high impact on buildings' energy consumption and users' comfort. During the past decades, office and commercial buildings were usually linked to the image of the international style and highly glazed facades. Nevertheless, since the oil crisis in the 1970s, green architecture and green design became more popular and building designs moved towards incorporating more solidity, more insulation, and building facades that can efficiently depend on natural air instead of heavily depending on mechanical ventilation. This movement aims at keeping the pleasant modern look by strategically locating windows where natural light penetration is actually required, in contrast to wrapping the building skin in glazing (Shuttleworth 2008).

In order to enhance the façade performance and hence decrease the total building energy consumption and environmental impact, several previous research works aimed at providing design guidelines for low-energy buildings. The impact of fundamental design strategies such as building orientation, window-to-wall ratio, glazing type and fixed exterior shading on annual energy use and daylighting performance has been thoroughly analyzed by several studies conducted in the past decades. Hausladen et al. (2008) investigated the effect of building facades on energy use. Different strategies and their effect on natural daylighting were inspected in the report of the IES task 21 "Daylight in buildings" (Ruck et al. 2000). The Center for Built Environment at the University of California, Berkeley carried out another research on high-performance facades, which lead to several reports and findings (Zelenay et al. 2011). Herzog et al. (2004) provided a façade construction manual that did not only focus on the performance of different materials of the building facades but also investigated some of the newer concepts such as double facades, solar facades, and manipulators. While most of these research works provide useful rules of thumb and general guidelines to follow, they focused on providing guidelines for conventional and modular buildings as it cannot take into consideration complex building design and the infinite options of façade shapes.

Modern building facades can have geometries and forms with a higher degree of complexity due to the recent advancements in computational tools, which enable architects and designers to develop performative designs that are tailored for more specific design problems and are driven from the building's necessities, surroundings, and context.

Many researchers worked on enhancing the building form with the aid of environmental simulation tools as well as optimization tools. While the use of optimization algorithms in the engineering field dates back to the 1980s, it didn't become common among researchers in architecture and the building construction field until the early 2000s (Abraham et al. 2005). Some of the early works on using optimization tools in buildings design was presented by Caldas and Norford (2002; 2003). In their research, a new optimization tool based on a Genetic Algorithm (GA) was used to optimize the size and placement of windows, the composition of building walls, the building form, and the design and operation of HVAC. Another recent research tackled the issue of performance-based exploration of facade designs by using a daylighting simulation software as well as a GA-based optimization (Gagne and Andersen 2010). A different research also used GA optimization without being restricted to simple geometries; it introduced a new method to control building forms by defining a hierarchical relationship between geometry points to allow the user to explore the building geometry without being restricted to a box or simple form (Yi and Malkawi 2009). Wright et al. (2013) explored the use of multi-objective optimization to minimize the energy and capital cost of a cellular designed façade.

While most of the previous tools and experiments were found useful at arriving at optimal designs, it is not easy to use by inexperienced users or researchers, and the optimization results are not easy to be analyzed.

1.2 Problem statement

Evaluating the holistic performance of alternative building facades during the early design phase can be very challenging to architects and designers. Building simulation software and design guidelines can help in overcoming simpler design problems. However, with a huge pool of passive and active strategies and technological advances to choose from and nonconventional construction methods, it becomes harder to analyze the numerous design alternatives. Moreover, when many objectives are targeted, it becomes more challenging to analyze and understand the trade-offs between the several objectives. Developing a simplified early design decision-support tools (DDS) to guide the designers through the complexity of analyzing the façade performance and reach high-performance designs is of immense importance.

1.3 Research objectives

The main aim of the thesis is to develop a framework and a design decision support tool to aid designers in evaluating and optimizing the integrated environmental performance of building facades in the early design stages.

The thesis has the following objectives:

1. Analyze and define passive and active strategies for high-performance building facades.
2. Analyze the state-of-the-art of the current design decision support and building performance optimization tools and frameworks.
3. Develop a framework for a holistic assessment of the integrated environmental performance of building facades.
4. Develop and validate a framework for optimizing the integrated performance of building facades.
5. Develop a decision support tool, with which designers can effectively compare and evaluate design alternatives.

1.4 Methodology

This research aims at developing a design decision support tool. Developing such tool requires an iterative process and methodology. For that reason, this research follows a Design Research Methodology (DRM). Unlike other natural and social science methodologies that attempt to understand and explain reality, design science methodologies try to create tools that serve human purposes. DRMs are developed and used heavily in the domain of software engineering and product design. For instance, a detailed Design Research Science Methodology (DRSM) was presented by Peffers et al. (2007) for conducting design science research in the area of information system. It consisted of six consecutive steps which are: Identify problem and motivation; Define objectives for a solution; Design and Development; Demonstration; Evaluation; and Communication.

Blessing and Chakrabarti (2009) developed another DRM in which more focus was given to the definition of the problem. This DRM is particularly useful with research that aims at presenting a proof of concept rather than a market-end product as the weight is shifted from the evaluation phase to the understanding phase. This methodology, which will be used in this thesis, consists of four stages: Research Clarification; Descriptive Study I; Prescriptive Study I; and Descriptive Study II. (Figure 1.4-1).

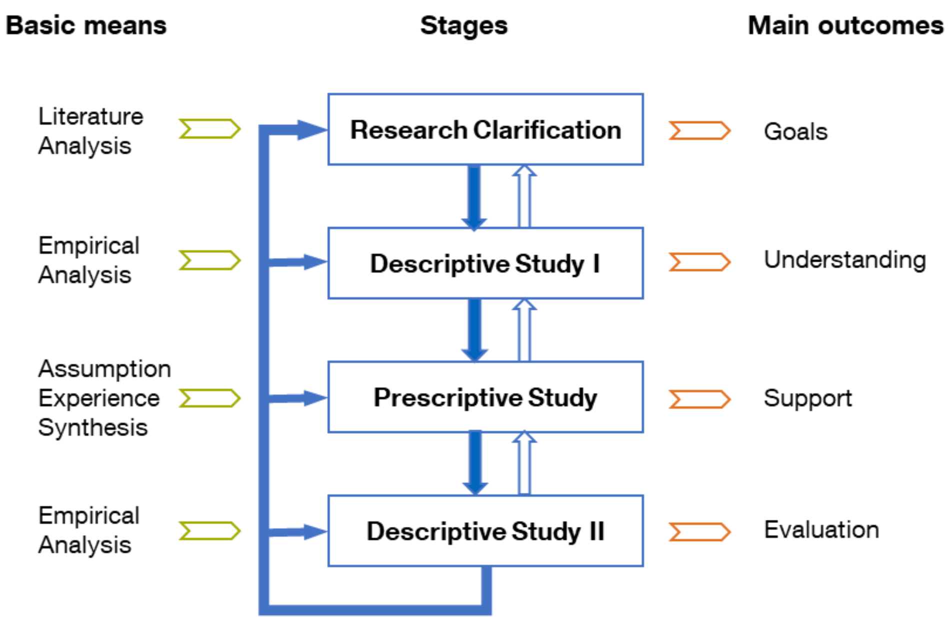

Figure 1.4-1

The Design Research Methodology (DRM) as suggested by (Blessing and Chakrabarti 2009)

1.4.1 Design research methodology stages

Research Clarification:

In the research clarification phase, related literature and previous studies are analyzed in order to better identify the research problem and research gap that the research is going to address, determine the approach to be used and define the expected goals of the research.

Descriptive Study I:

The aim of this phase is to create a clearer and deeper understanding of the research problem. Empirical analyses, such as case studies, are carried out to show the limitations in current tools that need to be addressed. It provides more information on the goals, which the developed tool should achieve and the problems it should overcome.

Prescriptive Study:

In this phase, the first prototype and conceptual design of the DDS tool are developed. Building on the knowledge and information gained from the previous phases, a proof-of-the-concept tool is designed and presented. A detailed, transparent and explicit explanation of how the framework functions, what the inputs and outputs are, and what to expect from the tool is provided.

Descriptive Study II:

This phase investigates the impact of the support tool and its ability to realize the desired goals. The evaluation is carried out through self-assessment using case studies and by disseminating the resulting tool with a wider and diverse group of users. The feedback is then used to enhance and improve the prototype.

1.5 Research outline

The PhD project was developed in four consecutive stages that imitate the four DRM stages discussed in the previous section. The first stage included defining the research aims and objectives as well as a comprehensive literature review on high-performance façade strategies and state-of-the-art design decision tools (Chapters 1,2 and 3). The second stage focused on the framework design and analysis using case studies (Chapters 4 and 5). The third stage of the project aimed at enriching the framework by developing a design decision support tool for integrative performance optimization (Chapter 6). The developed tool was then evaluated in the fourth and last stage of this research, which includes the evaluation of the framework using case studies and users' evaluation (Chapter 7).

Stage 1: Preparation (Chapter 1, 2 and 3)

Main objective: Analyze and define passive and active strategies for high-performance building facades, building performance assessment tools and metrics, as well as the state-of-the-art building performance optimization and design decision support tools.

This stage responds to the research clarification in the Design Research Methodology. In this stage, an extensive literature review was conducted with a twofold goal. First, the research scope and limitations are defined by analyzing and conducting a literature study on the strategies used in high-performance facades as well as the performance aspects and assessment tools and metrics (Chapter 2). The second part focused on the state-of-the-art tools and frameworks in the fields of building performance simulation, building performance optimization, and design decision support tools. (Chapter 3). The results of the literature reviews were used for defining the research problem and objectives.

Stage 2: Analytical phase (Chapter 4 and 5)

Main objective: Define a framework for a holistic assessment of building facades and analyze its limitations.

A framework for evaluating and optimizing the integrative façade performance was developed and tested using two case studies. The developed framework provides a method for the assessment of the building's façade integrated performance which includes: Energy use analysis, daylighting performance analysis, visual comfort and view analysis, thermal comfort analysis, as well as BIPV energy generation assessment.

Stage 3: Application (Chapter 6)

Main objective: Develop a design decision support tool, with which designers can effectively compare and evaluate design alternatives.

In this stage, a prototype for a design decision support tool was developed. An integrated performance dashboard was added to the framework as a design exploration tool. Using the dashboard, the designers can investigate the impact of their design changes on the different performance aspects, as well as comparing unique design alternatives and optimizations.

Stage 4: Evaluation and enhancements (Chapter 7)

Main objective: Evaluate the developed framework in optimizing the integrated performance of building facades.

The final stage of the project aimed at the testing and evaluation of the framework. In this stage, the decision-support tool was enhanced and simplified to be more useful and easier to use by architects and designers. Different focus groups of architects, engineers and designers were targeted to provide critical feedback on the development of the tool. Moreover, an integrative case study was used to evaluate the usefulness of the framework in achieving higher performance designs.

1.6 Structure of the thesis

Chapter 1 - Introduction

provides the background of the research, the problem statement, objectives, research design, and framework, as well as the methodology and the outline and structure of the thesis.

Chapter 2 – High-Performance Facades

explores the development and role of modern commercial building facades. The distinct functions related to the environmental performance are highlighted and passive as well as active design strategies are discussed and summarized.

Chapter 3 – Design Decision Support Tools

provides an overview of the several types of early design decision support tools. The advantages and disadvantages of each type are discussed, and recent developments and state-of-the-art are analyzed. A literature review on recent research aiming to develop comprehensive decision support tools is also presented.

Chapter 4 - Integrated Performance Optimization Framework

This chapter presents a framework for holistic environmental performance assessments as well as multi-objective optimization for building facades. The main concept behind the framework is discussed. Furthermore, the tools, simulation\calculation methods, and criteria used in the framework are presented.

Chapter 5 – Case Studies

The aim of this chapter is to examine the usefulness and effectivity of the framework in helping designers to achieve high-performance façade designs. Two case studies were conducted with a similar approach but different objectives.

Chapter 6 – Visualization Dashboard

This chapter presents a visualization tool prototype that can be effective in decision making and in the analysis of multi-objective optimizations results.

Chapter 7 – Framework Evaluation

In this chapter, the framework was evaluated by user representatives in focus groups as well as a comprehensive case study. Moreover, further enhancements of the framework were presented.

Figure 1.6-1

Thesis structure

Chapter 2: High-Performance Facades

2.1 Introduction

Computational tools and technologies play a key role in the design of today's building facades, whether in its form and geometry or the selection of materials and integrated systems. Facades are no more the mere protective skin it used to be. Technological influence can be seen in the development and increase in 3D printed facades, parametric systems, breathable and green facades, and interactive facades. This research focuses on climate-based building facades, which are facades that function as a filter between the exterior and interior and create comfortable interior living conditions. In order to achieve that, building facades have to achieve several functions, such as controlling the indoor thermal and lighting conditions, provide better visual contact to the outdoors, helping in insulating the building in order to reduce energy consumption and even being used as an active system to produce energy. With the current sophisticated design tools, numerous façade forms and designs can be easily obtained. However, it is important for designers and architects to understand the effect of their design decisions on the overall performance of the building. In order to have a clear understanding of the separate roles and functions of modern high-performance facades, it's vital to understand how the façade, as an essential building element, evolved into its current state. The following sections discuss briefly the evolution of modern façade as well as its diverse functions, especially those related to the environmental performance of the façade, and the different methods and metrics used for the assessment of the façade environmental performance.

2.2 The evolution of modern facade

The modern façade is a product of hundreds of years of continued development. The evolution process of the façade's form and function is connected to the history of humanity itself. Humans at the early ages discovered the importance of shelters that functioned as an enclosed envelope for protection and security. For centuries, wall-openings were limited by the difficulty to punch an opening in a load-bearing wall and for the main reason of security. Additionally, as using glass or similar materials was a rarity by that time the wall-openings were a major source of energy loss and vulnerability to climatic phenomena (Schittich et al. 2006).

In order to have more openings and wider spans, separating the building skin and the structural elements was essential. However, it wasn't until the industrial revolution that real opportunities emerged. Facilitated by the new technological advances in iron and glass manufacturing, buildings that integrate more transparency started to appear. It was, however, limited to specific building types such as factories, exhibition- and showrooms, and greenhouses. One of the most significant buildings that mark this time was Joseph Paxton's Crystal Palace, which was built for the London World Fair in 1851. The Crystal Palace was as much a technological miracle as an architectural one. Taking advantage of new glass sheet manufacturing, Paxton designed an almost fully transparent building that had the impressive final dimensions of 563 m long by 139 m wide and 41 m high. The structural understanding and approach used in the Crystal Palace buildings paved the way for the development of curtain walls (Figure 2.2-1).

In 1913 Walter Gropius and Adolf Meyer achieved another milestone in the history of modern façade development by designing and constructing the Fagus Werk building, a fully transparent shoe factory with structure free corners demonstrating a new concept of a "curtain wall". (Figure 2.2-2). Almost at the same time when several transparent facades started to emerge in the United States and more specifically in the new high-rise buildings in Chicago. The new highly-glazed towers presented a unique image at the time and promoted a style of steel-frame dependency which was later known as the "Chicago school". This style would continue unhindered for several decades for offices and workshops, where more workplaces were needed and the increase in daylight and illumination was appreciated. Highly glazed building with concrete and/or steel core construction would be, and to some extent still is today, the image of modernity and prosperity around the globe.

Figure 2.2-1

Exterior of the Crystal Palace at Sydenham, 1854.

Image source: paul-mellon-centre.ac.uk

Figure 2.2-2

Fagus Werk (1911-1913) by Walter Gropius and Adolf Meyer

Image source: Wikipedia.de

It was not until the 1970s, when the energy crisis hit, that voices against the ‘International Style” were raised. The former style known for its significant energy use and dependency on mechanical air conditioning was finally facing a fair amount of criticism. A new trend that shifts the focus on energy use and indoor comfort appeared and started to define new needs for building designers and industry. Several design and engineering solutions evolved to achieve the new goals, e.g. integrating elements of high-tech industry and technology into building design (Schittich et al. 2006), reducing the amount of glazing, and adding thermal separation in the window profile to limit thermal bridges and heat transfer (Arasteh 1985). Figures (2.2-3 and 2.2-4) shows a good example of the evolution of building’s façade over the last century. The *618 S Michigan Ave* building was constructed on 1913, but the façade was replaced with a fully glazed tinted curtain wall when IBM took over the building in the 1950’s to express the company’s ultra-modern image. Recently in 2012, the building was reacquired by Columbia University and the old façade was restored, and a new curtain wall was introduced as a second skin to provide better energy performance of the building and retain the transparent image.

Figure 2.2-3

The evolution of the same building's façade through 100 years' period. 618 S Michigan Ave, Columbia College Chicago. Illinois, Chicago, USA.

Architect: William Carbys Zimmerman (1913). Renovation: Gensler (2012)

Figure 2.2-4

The current façade of 618 S Michigan Ave embracing the original design while providing a second skin for high performance.

2.3 The role and functions of building facades

Building facades is the layer separating the interior of the building from the exterior. Herzog et al. (2004) presented an analysis for the function of the building façade as a separator between the interior and occupant comfort and the external nature. It provided an integral approach that combines passive and active functions to insure achieving its goals. (Figure 2.3-1).

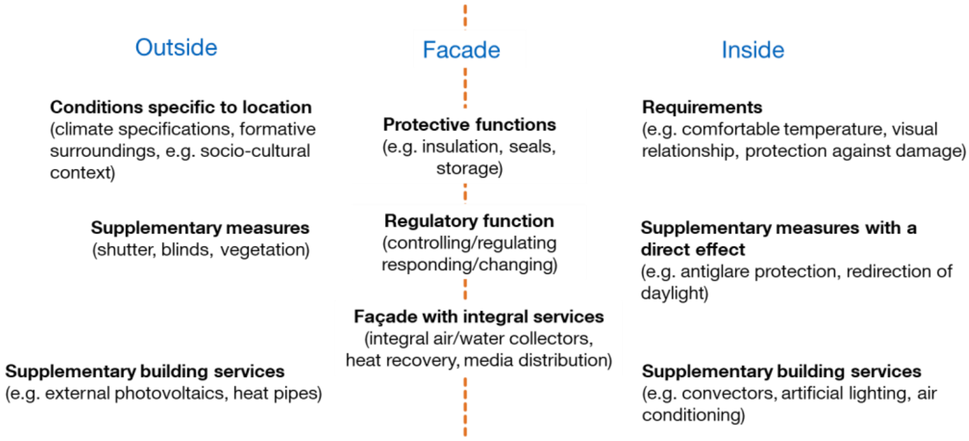

Figure 2.3-1

Requirement of building facade a separator between the "inside" and "outside" according to (Herzog et al. 2004)

Building facades are complex systems with many functions to fulfil. These functions can be grouped under some larger categories to be easier to analyze. Assuming the roof and façade as a single entity “building skin”, Lang (2006) divided the skin into different systems, which functions within a larger scheme that aims to achieve several functions such as:

- Lighting
- Insulation against heat / cold
- Sun protection
- Glare protection
- Visual contact / transparency
- Prevention of mechanical damage
- Energy gain
- Ventilation
- Protection from humidity
- Wind protection
- Visual protection
- Safety / security
- Noise protection
- Fire protection

A more detailed scheme was later provided as a function tree by (Klein 2013) based on a graduation project work by (Hövels 2007). The “Function Tree” was categorized into six primary functions and several secondary, supporting and detailed supporting functions. The six primary functions are:

- Create a durable construction
- Allow reasonable building methods
- Provide a comfortable interior climate
- Responsible handling in terms of sustainability
- Support use of the building
- Spatial formation of façade

The full scheme of two of the primary functions: Provide a comfortable interior climate and Responsible handling in terms of sustainability is shown in figure (2.3-2) below.

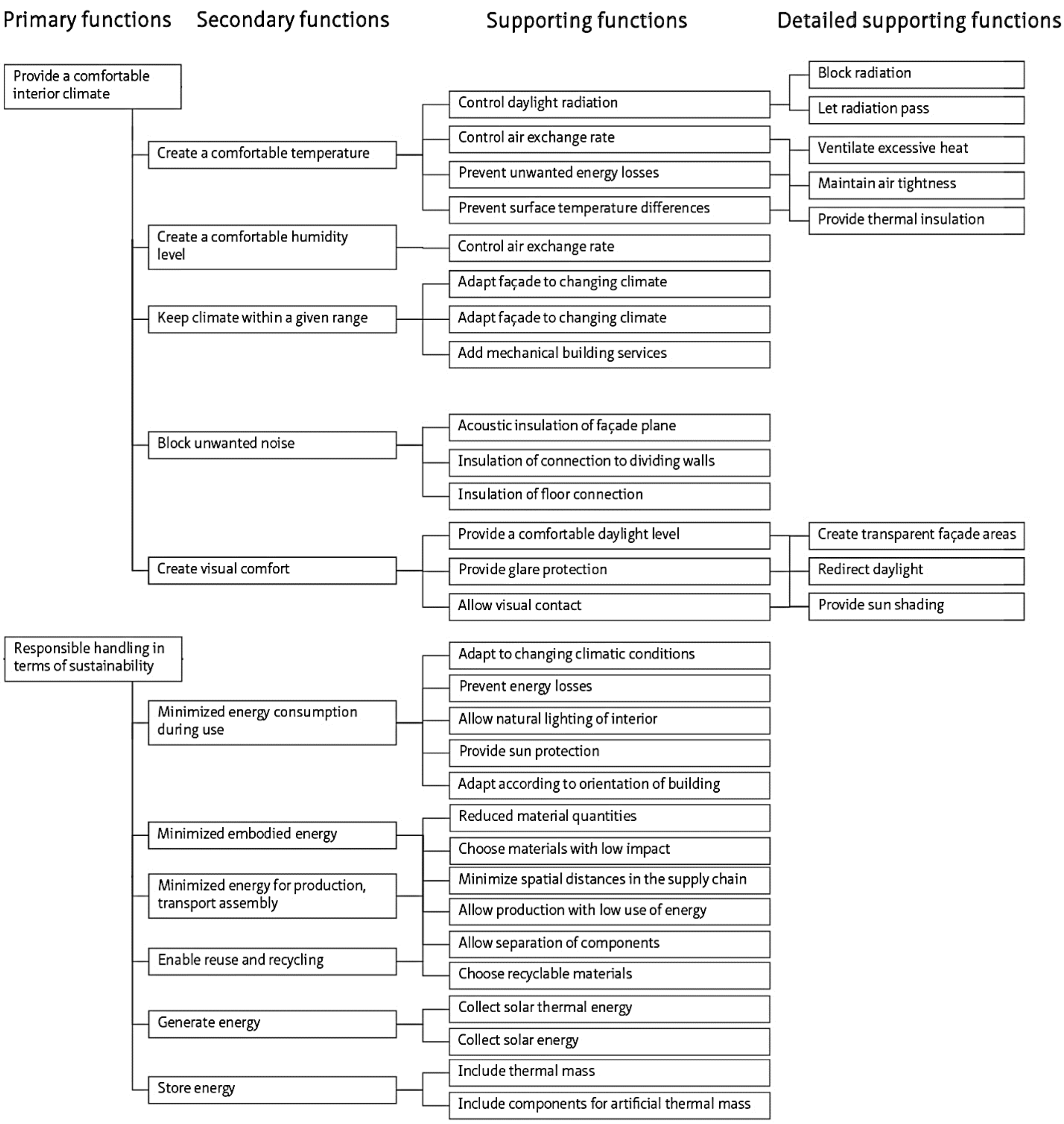

Figure 2.3-2

An excerpt from the façade function tree as presented by (Klein 2013)

2.4 Performance parameters

High-performance facades can have various definitions depending on the scope and type of performance implied. For instance, façade performance can refer to the structure, or the energy performance of the facade. This thesis focuses on the holistic environmental performance of the building, which includes the relation between the environment, the façade and the user. In that context a high-performance façade can be defined as " *… an exterior enclosure that uses the least possible amount of energy to maintain a comfortable interior environment, which promotes the health and productivity of the building's occupants.*" (Aksamija 2013). The performance of a building façade is therefore firmly related to how effective the facade performs for its various functions that are related to the user's comfort and environmental impact.

From the literature, performance parameters that are related to environmental performance of building facades can be summarized without a particular order as: thermal comfort, visual comfort, energy use, daylighting, environmental impact and energy generation. (Figure 2.4-1).

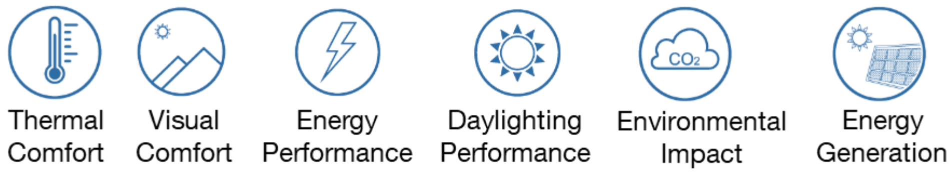

Figure 2.4-1

Performance parameters of building Façades

2.4.1 Thermal comfort:

Thermal comfort is an essential aspect in modern office space and is usually directly linked to the productivity of workers (McCartney and Humphreys 2002). According to the ISO (EVS-EN ISO 7730:2005) standard, thermal comfort is described as being "*… that condition of mind which expresses satisfaction with the thermal environment.*" While the definition may be clear and concise, achieving that goal in a qualitative and quantitative measuring is not an easy task. Thermal comfort depends on several parameters that cannot be easily unified between coworkers, which makes it harder to measure the thermal comfort as each person has a different perception of comfort. One way to overcome this issue is to use statistical models that represents the different users of the space. One of the most used models to measure thermal comfort is the Predicted Mean Vote (PMV) model presented by Fanger (1970) which is still widely used till date. The PMV model uses a scale from -3 (cold) to +3 (hot) to determine the thermal sensation. The recommended acceptable PMV range for thermal comfort from ASHRAE (Standard 55-2010) is between -0.5 and +0.5 for an interior space. When the PMV is defined, the predicted percentage of dissatisfied (PPD) can be calculated, and benchmarks of indoor environment can be set. ISO7730 (2005) suggests that an average performing building should be designed to meet the criteria of less than 10% PPD. Later studies showed that the PMV model works well with air-conditioned buildings. However, in naturally ventilated and mixed mode buildings, people tend to adapt with higher indoor temperature than those predicted by the PMV model (Richard de Dear and G. S. Brager 1998). As a result another "adaptive" model was developed based on hundreds of field studies where persons can dynamically interact with the environment (Nicol and Humphreys 2002). These findings later encouraged the ASHRAE to make significant revisions in its comfort standard and include the adaptive comfort standard (ACS) (G. S. Brager and R. de Dear 2001).

For both models, the parameters that are used to calculate the PMV and PPD are:

Metabolic rate (met): Energy generated by human body. The metabolic rate is dependent, among other things, on the activity of the person.

Clothing insulation (clo): The amount of thermal insulation the person is wearing.

Air temperature: The temperature of indoor air surrounding the person.

Radiant temperature: The temperature of the surrounding surfaces.

Relative humidity: Percentage of water vapor in air.

Air velocity: Rate of air movement in a given time.

2.4.2 Visual comfort

Visual comfort is also an essential design parameter in commercial buildings. Modern offices depend on a constant use of monitors and visual aids, which requires homogenous lighting and glare free spaces. Similarly, the view to the outdoors plays a key role in the well-being and satisfaction of the occupants.

Glare analysis

Glare occurs because of high contrast between the luminance of the task area and the surrounding area. Having inhomogeneous lighting in the field of view with high contrast lighting spots can result in inconvenience and inability to focus. With the everyday use of computer screens in offices, avoiding glare is very important as having too much light on the screen will make it harder to work, and users will most certainly close the blinds and depend on artificial lighting. Several methods with variant complexity could be used for glare assessment such as:

Maximum to Minimum Illuminance Ratios provide a method that can help detect glare and unbalanced illuminance on the work plane. A work plane calculation must be performed to find the point illuminance at the desired time of year or the averages based on an annual calculation. Then computer simulation is carried out to find the work plane extremes so the maximum to minimum illuminance ratio can be calculated.

Daylight Glare Index (DGI) is the first metric to consider large glare sources such as sky viewed through the window. However, direct sunlight and reflections are typically not accounted for, but they can be.

CIE Glare Index (CGI) was widely used and adopted by the International Commission on Illumination (CIE). Calculations require both direct and diffuse illuminances and are mainly used for luminaire sources of glare.

CIE Unified Glare Rating (UGR) Established by CIE in 1995 is a simplified method of CGI now preferred by the CIE. The separation of direct and diffuse illuminances is no longer needed. (ICE 1995)

Finally, **the Daylight Glare Probability (DGP)** DGP represents the probability that a person is disturbed by glare and is derived from a subjective user evaluation (Wienold 2009; Wienold and Christoffersen 2006) . Annual DGP uses a simplified method that calculates the vertical illuminance at the eye level as a parameter which can affect the brightness of the space. (Kleindienst and Andersen 2009).

View to outdoors

View to the outside is more than often left out during the design, despite the undoubted importance of view and effects on users (Leather et al. 1998; Heschong Mahone Group 2003). Hellinga and Hordijk (2014) attributes this to the reasons that research on daylighting and view quality belongs to different research disciplines and secondly, there is usually very limited time and budget for architects and engineers to work on daylighting and view. Hellinga and Hordijk also found that users prefer distant and nature views and views that contain water. In design cases were view is an essential concern, such as spaces overlooking important landmarks or natural features, such as the case presented in the first case study in Chapter 5 of this thesis, the view to the outside cannot be neglected. It can be noted that only few studies considered the view as one of the main objectives of building façade design and in particular shading devices design (Konstantzos et al. 2015; Tzempelikos 2008; Kim and Kim 2010; Sherif et al. 2016). Evaluating the view to the outdoors can be a very hard task as it combines both qualitative and quantitative measures. Measuring the view-to-outdoor percentage can be done using various methods from simply measuring the percentage of windows to external walls to measure the percentage of view lines to a specific point (landmark) outside the window. In this thesis a 3D isovist method was utilized. An isovist field is "… the set of all points visible from a given vantage point in space and with respect to an environment." (Benedikt 1979). Assessing the quality of the view is, on contrary, a more challenging task as it requires the knowledge of the surrounding of the buildings and the exact image that the occupant of the space sees from the room. Hellinga (2013) developed a point system to assess the view based on survey of building occupants.

2.4.3 Daylighting

The optimized use of natural daylighting can lead to significant energy savings while offering a productive friendly environment for users. Daylight availability, the absence of glare and direct sun, and view to outdoors can have direct and in-direct effects on users' comfort and productivity. Natural daylight was found to strongly affect the health, mood and behavior of occupants. Past studies of shift workers have shown that decreased exposure to daylight is strongly correlated with an increased risk of health problems (Webb 2006). Studies of stress levels among people working indoors indicate that workers working under daylight have considerably lower stress levels than those working under artificial lighting. (van Bommel, Wout J M 2006). A survey of building occupants found that daylight is perceived considerably better for physiological comfort and health, and somewhat better for work performance (Heerwagen and Heerwagen 1986). A more recent study on the effect of windows on workers' performance highlighted the effect of both the availability of views and daylighting on workers' performance (Heschong Mahone Group 2003).

Most of architecture design decision related to natural daylight are based on illuminance measurements of the space, usually on a horizontal plane that represents the working plane. Building codes and rating systems define a minimum amount of lighting, which differs according to the use of the space. Measuring methods differs from a single-point-in a time to annual measurements. Quantitative daylight metrics are usually used for measuring the internal illuminance of the space either in specific moment or annually for a certain measuring plane.

Daylight Factor (DF) is defined as the ratio of the internal illuminance at a work-plane point in a building to the un-shaded, external horizontal illuminance under an overcast sky as defined by CIE (International Commission on Illumination). Daylight Factor was mainly proposed for overcast sky condition and therefore cannot be used under other sky conditions as it does not account for orientation, shading and glare control, or changes in sky conditions. Moreover, the daylight factor was never meant to be a measure of good daylighting design but as a minimum legal lighting requirement.

Single Point in Time (SPT) In this method illuminance calculation is measured at a specific surface for a single time of the year. The time can be selected to represent an average daylight condition, such as sunny equinox at noon or an extreme scenario, such as cloudy winter solstice. This method is widely used and accepted in several codes and certification programs such as LEED as it accounts for variability in designs such as orientation and shading mechanisms. However, with the increase of mixed-use spaces and changes in the functions of buildings, it’s highly recommended to account for different measuring times that represent the different conditions throughout the entire year. Therefore, annual dynamic metrics were presented.

Dynamic Daylight Performance Metrics (DDPM) or **Climate Based Daylight Metrics (CBDM)** was recently proposed and offers an excellent chance to evaluate the daylighting performance on year-round basis. The method quantifies the amount of daylight available in a space based on annual illuminance or luminance profiles. These values are generated from a weather file and are utilized through hours of occupancy. An important advantage of dynamic daylight performance metrics is that it considers the quantity and character of daily and seasonal variations of daylight for a given building site. (Reinhart et al. 2006).

Some of the often-used dynamic daylight metrics are:

Daylight Autonomy (DA) is "the percentage of the occupied hours of the year when a minimum illuminance threshold is met by daylight alone" (Reinhart and Walkenhorst 2001).

Continuous Daylight Autonomy (DAcon) is a modified version of the daylight autonomy metric. Continuous Daylight Autonomy gives partial count to times when the daylight illuminance at a given point lies below the task/ambient lighting threshold. This method becomes useful for showing the potential energy savings if the electric lights have dimming or multi-level switching capabilities.

Useful Daylight Illuminance (UDI) is another proposed annual daylight metric, as the name indicates, UDI calculates the total number of occupied hours that "useful" daylight enters a space at a select point. Useful daylight is defined as providing ambient light at the work plane at illuminance levels between 100 lx to 2,000 lx. Above 2,000 lx, heat gains and glare become potential problems. The UDI metrics uses thresholds (too low, useful, and too high) for certain percentages of the work plane. (Nabil and Mardaljevic 2006).

IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) is a recent method that corresponds to the Illuminating Engineering Society standard IES LM- 83-12 (IESNA 2012). Normally, $sDA_{300Lux/50\%}$ is used to evaluate the presence of sufficient daylight by calculating the percentage of the floor area that receives 300 lux or more for at least 50% of the annual occupied hours, while ASE represents the percentage of the floor area that receives more than 1000 lux for at least 250 occupied hours per year.

2.4.4 Minimize energy consumption

Probably the most sought-after aspect, minimizing energy use is a main goal in most high-performance buildings. Energy efficiency is the ratio between the energy output and input. The efficiency is related to the amount of energy that is being lost during the processes. Most industrial countries now have building regulations that enforce at least a basic set of energy conservation measures. The largest part of energy is usually consumed during operational phase by the heating and cooling systems or HVAC system. Artificial lighting and equipment loads also contribute to the total amount of energy consumed. Some design solutions that aim to minimize the energy use have become self-evident: use of thermal isolation, minimization of air gaps, avoidance of thermal bridges, solar orientation and application of energy-efficient HVAC-systems are daily practice.

The 2010 Energy Performance of Buildings Directive (EPBD) requires that by the end of 2020 'all new buildings are nearly zero- energy buildings' (nZEB). A 'nearly zero-energy building' is defined as a building that requires nearly zero or very low amount of energy, which should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby (European Parliament, Council of the European Union 2010). Beside codes and laws, several green building certification systems were developed to guide designers and architects to achieve higher performance building designs. Of the most popular certification systems are LEED, BREEAM, DGNB, and PassivHaus.

2.4.5 Minimize environmental impact

Buildings don't only consume energy while operating. A significant amount of energy is used throughout the life-span of the building starting with the acquisition of raw materials, the production and manufacturing of building elements, construction work processes, and actual use of the building including maintenance, refurbishment and operation and finally, at the end of life, deconstruction or demolition, waste processing and recycling. The energy used in other phases other than the operational phase is usually referred to as embodied energy or grey energy, and while the EPBD requires the energy use during operation phase is minimized, other phases in the building life cycle neglected (Szalay 2007). In a net-zero energy building the embodied energy will count for nearly 100% of the total energy use during the building life span. Which means that only conceivable way to move forward is then to limit the amount of energy used during the other phases of the building construction. One of the methods to measure the embodied energy in building elements is by using the Life Cycle Assessment (LCA) approach.

Table 2.4-1

Life cycle stages of buildings from (BS EN-15978:2011)

Product			Construction		Use Stage							End of Life				Benefits and loads beyond the system boundry
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Construction	Use	Maintanence	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Demolition	Transport	Waste processing	Disposal	Re-use recovery and recycling potential

In the life cycle assessment, the amount of the all materials used in the building elements is calculated. Information about the energy used in the different phases of the building element production to the end of life phase is gathered and compiled. Information related to embodied energy is usually provided by the products manufacturer. Efforts toward creating an inventory of materials' embodied energy have resulted in different databases. Commercial databases such as GaBi and ecoinvent are considered the most complete and transparent datasets (Martínez-Rocamora et al. 2016; Takano et al. 2014). Other open-source datasets also exist such as the environmental product declarations database ÖKOBAUDAT (BBSR 2015), used in the German sustainable building certification scheme, DGNB. However, such databases are limited by regional standards and selection of products and are usually limited to specific phases of the building life span.

In the building industry, embodied energy is most frequently expressed in mega joule (MJ). Several other indicators are often used to evaluate the materials impact on the environment such as:

PERT Total renewable primary energy

PENRT Total non-renewable primary energy

GWP Global warming potential for a time horizon of 100 years

EP Eutrophication potential

AP Acidification potential

ODP Ozone layer depletion potential

POCP Photochemical ozone creation potential

ADPE Abiotic resource depletion potential for elements

2.4.6 Generate energy

To achieve a near zero energy or net zero energy, renewable energy has to be generated on site. Musall et al. (2010) conducted a survey of more than 280 net-zero energy buildings within the framework of the International Energy Agency IEA Task 40/ Annex 52 "Towards Net Zero Energy Solar Buildings" and found that all cases depend on PV generated electricity to achieve the net-zero energy benchmark. Both the roof and façade can aid in generating renewable energy using integrated PV cells. Different systems can be used depending on the type of construction and the context. Energy generation output varies significantly due to the type of PV cells used, the total area, orientation, inclining and tilting angle as well as the efficiency of the system. (Attia and Herde 2010).

2.4.7 Holistic approach

Several research and practice works focus on a specific environmental measure. However, a better way to deal with façade designs is through an integrative and holistic approach. Any design decision or strategy is more likely to affect several measures at once. Considering the complexity of the façade system, such an approach is important to fully understand the trade-offs resulting from design decisions. The following table summarizes this section by connecting the performance aspects and measuring metrics and indicators and highlighting the ones that were used in this research.

Figure 2.4-2

Representation of the mutual connections and relations between the environmental performance aspects.

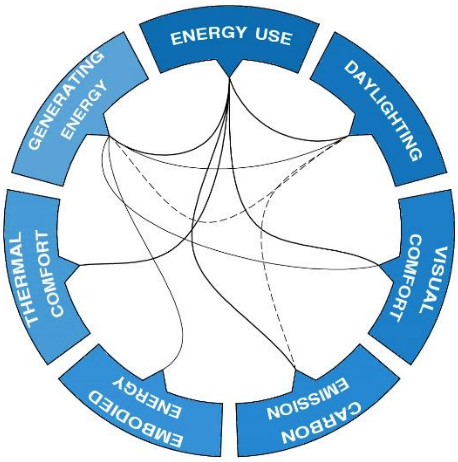

Table 2.4-2

Environmental performance aspects and its assessment metrics and indicators. Indicators highlighted in bold and blue were the ones used in this research.

Environmental performance aspect	**Models/Metrics and Indicators [units]**
Thermal comfort	Predicted Mean Vote (PMV): **PMV [%]** **PPD [%]**
Visual comfort	Glare analysis: Daylight Glare Index (DGI) [%] CIE Glare Index (CGI) [%] CIE Unified Glare Rating (UGR) [%] **Daylight Glare Probability (DGP) [%]** View analysis: WWR [%] **3D Isovist [%]**
Daylighting	Daylight Factor (DF) [%] Single Point in Time (SPT) [lux] LEED points [pts.] **Daylight Autonomy (DA) [%]** **Continuous Daylight Autonomy (DAcon) [%]** **Daylight availability (DAv) [%]** **Useful Daylight Illuminance (UDI) [%]** **Spatial Daylight Autonomy (sDA) [%]** **Annual Sunlight Exposure (ASE) [%]**
Energy consumption	Annual energy consumption [kWh/a] **Energy Use Intensity (EUI) [kWh/m2/year]** Annual thermal load [kWh/a] **Annual thermal load/unit area [kWh/m2/year]** Annual cooling/heating/lightning load [kWh/a] **Monthly cooling/heating/lightning load [kWh/a]**
Environmental impact	Total renewable primary energy (PERT) [MJ] **Total non-renewable primary energy (PENRT) [MJ]** **Global warming potential for a time horizon of 100 years (GWP) [kg CO2-eqv.]** Eutrophication potential (EP) [kg PO43-eqv.] Acidification potential (AP) [kg SO2-eqv.] Ozone layer depletion potential (ODP) [kg R11-eqv.] Photochemical ozone creation potential (POCP) [kg C2H4-eqv.] Abiotic resource depletion potential for elements (ADPE) [kg Sb-eqv.]
Energy generation	Annual DC Energy [kWh] **Annual AC Energy [kWh]**

Chapter 3: Design Decision Support Tools

3.1 Early design decision support tools

Providing sufficient information about the environmental performance of the design during early design stage is of significant importance. The building overall performance is more sensitive to changes made in early design as changes in later design stages are typically limited, more expensive and time consuming (Ritter et al. 2015), yet combining the different passive and active systems in early design phases is a complex and challenging task (Attia et al. 2012). Several types of decision support tools were developed throughout time to help designers and architects make informed decisions during the early design stage. The following sections discuss four different types: guidelines and rules of thumb, simulation tools, knowledge-based tools, and optimization tools.

3.2 Guidelines and rules of thumb

Guidelines and rules of thumb were the first methods used in guiding building design. It is typically consisting of generalized statements, charts, tables or diagrams based on extensive empirical research. Its aim is to provide a simplified information and guidance to the designer. Simplifies rules of the thumb and design guidelines are still used till date by some codes and standards such as ASHRAE standards in the US and German Institute for Standardization (DIN) standards in Germany. It’s also widely used in building rating systems and certification programs such as LEED, BREEAM, DGNB and PassivHaus. Additionally, detailed handbooks are commonly used as designing aiding tools for architects, engineers and designers.

One of the first handbooks to provide guidelines and design tools related to the performance of the building was presented by (Olgyay 1963; Olgyay and Olgyay 1957). In his book *Designing with climate* Olgyay discussed the importance of climatic design and the impact of climate on building design and presenting guidelines for shading devices design using shading masks. G. Z. Brown presented another useful and easy to use guidelines in his book Sun, Wind, and Light (Brown 1985), in which he presented several approaches to aid designers who want to consider the climatic factors in the early stage in the design process. A third edition was published in 2014 providing more examples and updating the methods. In the book more than hundred techniques were presented and sorted according to climate, scale, and into bundles. In the book “Climate-skin: building skin concepts that can do more with less energy” (Hausladen et al. 2008), the authors suggest that at the early planning phase it is more necessary to make a quick assessment of the building façade and services, than detailed calculations. That is mainly because the boundary conditions and the building itself is still not strictly defined and several options are still there to consider. The book starts with a foundation of knowledge discussing the role of the building façade in different times of year and climates. It than discusses the role and the use of several façade concepts and technologies. Finally, the book concludes with design guidelines that are easy and quick to follow. Guidelines include recommendations for orientation, building position, building height, building shape, façade concept, size and proportion of the window area, solar screening, glazing quality, insulation standard, air change and ventilation, among many others. Despite the comprehensive and useful knowledge presented by the authors, the guidelines proposed are very generalized and can be seen better as palette of different façade concepts that can be used and decided by the architect according to the context. It aims to provide the designers with a better understanding of the effect of different façade elements than strict location- and case-based guidelines. In a later publication the authors presented a handbook for designers with a more direct approach. In the book “Building to suit the climate”, guidelines for building skins were introduced for each climate zone (Hausladen et al. 2011). Climate zones were divided into six zones: cold, temperate, subtropics, tropics, desert coastal and desert continental. For each climate zone a typical city was picked and guidelines for building structure, building skin, building systems and urban planning rules were presented. The book afterwards discusses the trade-off between the initial and running cost of each system and provides a glossary for the building concepts provided. This approach is most useful as it links the building guidelines with the climatic zones. Hindrichs and Daniels (2007) presented another guideline book that besides focusing on building skins extends to other areas such as renewable energy and solar technologies. The volume discusses in detail the newest technologies such as advanced façade and glazing systems and provides flowcharts to compare and provide an easy way for the selection of the suitable system. Another research conducted in the Lawrence Berkeley National Laboratory in the US and funded by the California Institute for Energy Efficiency (CIEE) concluded with online guideline and report for the design of windows and building facades in commercial buildings (O'Conner et al. 1997). While it mainly focuses on the aspect of daylighting, other factors such as the effect of windows on HVAC systems and costs were also considered in an integrated approach.

Such guidelines proved to be quick and useful in early design phases and are still used by students, teachers and practitioners. However, achieving maximum efficacy is hindered by several limitations. The guidelines are usually generalized from calculations of a typical space or prototype, it doesn't necessary take in concern the specific form, context and building systems used by the designers. That is very critical when non-standard spaces are being evaluated or when a unique context and design problem is at hand. In such cases using straight guidelines might lead to misinformed design decisions. It is the responsibility of the designers to make sure that the guidelines apply to the case at hand. When more accurate results related to the real-world design are needed, building simulations are believed to be more useful.

3.3 Building performance simulation

With the increasing complexity of the buildings' designs, simple rules of thumb and guidelines are no longer sufficient. To have a better understanding of the building performance, accurate calculations are to be made. This was also catalyzed by the fast and increasing advances in computational tools. Simulation is defined as the process of imitation of a real-life operation or a system over time. Mostly made by computer nowadays, the simulation process usually includes a representative model, mathematical models, or equations that describe the behavior; a method for solving these mathematical equations; and finally, a visualization of the results. Each step in the simulation process should be treated critically to ensure the accuracy of the results obtained. The simulation model has to be representative of the real object and has a degree of details that is sufficient for the simulation task. Simulation results are dependent on the accuracy of the mathematical models used. Finally, the visualization of the results should provide clear information to the user.

Simulations tools are developed for the assessment of nearly every aspect of the building performance such as: Energy analysis, daylighting, ventilation and indoor air quality and acoustics. The US dept. of Energy hosts a directory of building energy simulation tools (BEST) (US Dept. of Energy). According to (Attia et al. 2012) the number of building simulation tools at the previously mentioned directory increased from 107 to 389 between 1997 and 2010. Detailed reviews of simulation tools in the architecture design and building performance disciplines are presented by (Augenbroe 2001), (Crawley et al. 2008) and (Attia et al. 2012).

In the domain of building façade design, building simulation software is used extensively. A quick search on the database SCOPUS with the words “façade” and “simulation” results in nearly two thousand articles. Simulation tools were used for predicting and comparing the energy use (Thalfeldt et al. 2013; Rodriguez-Ubinas et al. 2014; Poirazis 2005; Petersen 2011; Raji et al. 2014) ; daylighting performance (Zhang et al. 2012; Zelenay 2011; Wagdy and Fathy 2015; Thomson 2011; Sherif et al. 2012); thermal comfort (Peters and Aksamija 2016; Mirrahimi et al. 2016); visual comfort (Matterson et al. 2013; Heim et al. 2012); and life cycle assessment (Stazi et al. 2012; Komerska et al. 2015; Lupíšek et al. 2015).

3.4 Building performance optimization

In a traditional optimization process, the minima or the maxima of a given function are found using special algorithms. This function, which is typically known as the objective function, may depend on any number of parameters, and any combination of parameter values within the defined search space is considered a feasible solution. The optimal solution will be the feasible set of parameters which minimizes (or maximizes) the objective function. A problem will not necessarily have one unique solution. It may have no optimal solutions at all, a finite number of solutions, or an infinite number of solutions, which can be defined as a more specific subset of the search space (Papalambros and Wilde 2000).

3.5 Multi-objective optimization

Multi-objective optimization deals with problems that have multiple objectives (Abbass et al. 2001). According to Coello (1999), most of the real-world decision problems are of multi-objective nature. However, there is no universally accepted definition of “optimum” for such problems as opposed to single-objective optimization problems. Normally, the decision on what the “best” answer corresponds to the so-called human decision maker. Multi-objective optimization breaks the complex system down into a number of elementary sub-systems. The solving procedure of a sub-system is often well known and easier to solve. In contrary to single objective optimization, multi-objective optimization doesn’t result in a single optimum solution, but a whole set of possible solutions of equivalent quality (Abraham et al. 2005). This approach is very relevant to the architecture design process where decisions are taken by considering the trade-offs between conflicting objects.

3.6 State-of-the-art in decision support tools for buildings performance Assessment and optimization

Because of the complexity of using optimization tools and the lack of efficient design decision support systems, a new research domain that focuses on developing decision support tools and frameworks emerged to support designers in creating well-informed and high-performance designs. A software tool, (COMFEN) that can aid in assessing the energy consequences of building design decisions, was developed by researchers at Lawrence Berkeley National Labs in California (Selkowitz et al. 2014). The tool provides a simple interface by which the designer can easily assess the performance of flexible fenestration façade designs. It is also possible to compare the simulation results in terms of energy use, daylighting, thermal comfort and CO2 emissions. The software uses its own 3D modeling engine, where the user can modify a shoe-box model and control the dimensions of the space as well as the main façade by drawing a fenestration system. In that sense, the user can not freely design the building form but is restricted to the rectangular form given by the software. The tool is also limited to specific climate locations mainly in the USA, Canada, and Australia. According to the site, the wall construction is defined by the ASHRAE default and cannot be changed by the user. Despite all the limitations, the COMFEN tool provides a good and fast method to compare fenestration systems effectively.

Turrin (2014) developed a framework to parametrically optimize large roofs with the aid of multi-objective optimization (MOO) and multi-disciplinary optimization (MDO). In her research, a three-parts design approach for the performance assessment of large roofs was developed with special focus on passive climatic comfort. The framework utilized a parametric CAD software and optimization tools. The usability of the framework was then tested with several practical and educational case studies. The main limitation of the framework lies in the use of several different tools without a unified tool or interface.

Another powerful decision making support framework was developed by Lin (2014), where a multi-disciplinary optimization (MDO) approach was also utilized to provide energy performance feedback in the early design stages. The Evolutionary Energy Performance Feedback for Designers (EEPFD) integrates several tools such as: Revit, Excel, and Green Building Studio. It proposes a framework where designers can integrate energy performance feedback to support their decision-making process during the early stages of design. It also provides feedback for other measures besides energy use such as financial or spatial programming compliance. Autodesk Revit serves as the parametric design platform, while Excel is used for the calculation of the three design objective scores. Finally, GBS is accessed through Revit's conceptual energy analysis and is used for energy simulation. The prototype tool, H.D.S. Beagle was also used to provide more simulations. The framework uses a modified genetic algorithm to drive the optimization process. (Lin and Gerber 2014; Lin and Gerber 2013). The framework was validated using hypothetical and pedagogical case studies as well as case studies from practice. Despite providing a coherent and complex framework, the EEPFD tool had several limitations including:

1. complexity of the framework and depending on manual intervention that requires a high level of experience with the framework.
2. Limits to geometric complexity from utilized platforms
3. Optimization speed

Asl (2015) presented an integrated framework for building multi-objective optimization for Building Information Modeling (BIM) software. The significance of the research is for developing the first multi-objective framework that is fully integrated within a BIM software. The framework depends on Autodesk Revit and Dynamo (an open source visual programming tool) to aid designers in modeling and exploring design alternatives. Assessment of building performance (Energy use and daylighting) was made by using Autodesk Green Studio, a built-in cloud-based simulation tool. The framework then utilizes an optimization tool (Optimo) to optimize the performance of the design (Rahmani Asl et al. 2015). The framework was validated and tested by using case studies by the authors and other users. The main limitation of the framework lies in the long time needed for the optimization process, the restriction in further expanding the framework using third-party tools, and the absence of an analysis and visualization medium for the proper representation of optimization results.

Shao et al. (2014) developed a model-based method to support design teams in early design stages. The study proposes a model-based method to support design teams in making informed multi-criteria decisions for energy efficiency solutions when retrofitting building facades. The main contribution lies in integrating a qualitative and quantitative analysis procedure carried out by the design team with a numerical multi-objective optimization carried out by computer. The analysis procedure contains a quality function deployment model (QFD), which allows the design team to identify and quantify stakeholders' concerns and needs. Based on this model an optimization model is set up. Afterward, an automated procedure explores this model by multi-criteria constrained optimization to deliver information on the design space. The model provides a basis for embedding quality function deployment and multi-objective optimization into the decision making of energy efficiency retrofit solutions, which considers the important role of the design team by carrying out the analysis procedure.

The main limitation of the study is the complexity of the model and the lack of a user-friendly interface. An integrated computer-based tool with a user-friendly interface between the model and the users has not been developed in this study. No guidance system was present or utilized to provide guidance to the users. Under this circumstance, expertise in the areas of building performance simulation, mathematical optimization and evaluation are required to implement the new approach.

Another research that focused on life cycle environmental impact was presented by Wang (2005). In this research, the object was to minimize the environmental impact and three impact categories were considered, which are resource depletion, global warming, and acidification. The framework consists of four parts: the input, the output, the optimizer and the simulation program. In the end, an object-oriented framework was presented and can be used for other uses. Nevertheless, the framework depends entirely on programming and no user-friendly interface was presented, which limits the possibility of being used by architects or designers. The lack of a guiding system and the long optimization time were also present as major limitations in the framework.

Winn (2014) presented another inter-scalar multivariant decision making framework. The computational design framework integrates analysis and optimization to inform decision-making in parametric architectural 3D modules. The workflow uses parametric modeling in grasshopper as the modeling base. A special visualization tool was developed to visualize climate characteristics based on the case location, which helps in determining the design variables. The models are then tested using third-party plugins and optimized, using a multi-objective genetic algorithm. The research uses several tools for visualizing results on 3D geometry for fast feedback for designers. The main limitation of the framework is the inconsistency and complexity depending on the task at hand. Visualization tools seem to be developed for each case separately and therefore there is no unified tool available for other users. Feedback on the efficiency and validation of the optimization framework was also not present.

Although not limited to building performance optimization, Vierlinger and Hofmann (2013) developed a framework for design search and optimization in parametric context. The developed optimization tool is available as a plugin for the parametric tool grasshopper and therefore is available for users to use in different design problems such as optimizing structure systems or walkability and urban zoning, ... etc. The developed plug-in Octopus is based on the evolutionary algorithm SPEA-2, developed at ETH Zurich (Zitzler et al. 2001) and applies evolutionary principles to provide Pareto-optimal solutions. It provides an interface to interact with the optimization process and a multi-dimensional scatter plot for the visualization of the results. However, some limitations affects the usability of the framework such as the long computation time and the difficulty in interpreting the optimization. Another limitation is the absence of any guidance or decision support tools as it is provided as a generic tool.

Konis et al. (2016) used the Octopus optimization plugin to present another framework for the optimization of passive performance and building form in the early design stages. The framework is multi-objective as it aims at improving the performance of daylighting, solar control, and natural ventilation strategies in the early design stages of architectural projects. The framework uses Grasshopper as the main modeling tool and developed a plugin to support easy modeling of building components, such as fenestrations and shadings. The models are then connected to simulation engines using third-party plugins. The Optimization was then carried out using the Octopus optimization plugin. The research provides a simple framework based on available tools to provide simulation-based multi-objective optimization for high-performance buildings. The main limitation of the research lies in the absence of proper visualization of the optimization results or guidance system tools.

3.7 Conclusion

Previous research work, that focused on developing design decision support tools for building performance optimization, resulted in a number of useful tools and frameworks for designers and architects. Several limitations were found to hinder the use of these tools in everyday practice. The main limitations found in the literature were:

Computation time: building performance optimization is a very time-consuming task. Having a huge number of cases to optimize increases the computation time significantly. The process becomes more complicated when different simulation types are run simultaneously (e.g. energy and daylighting).

Parametric Modeling: while several frameworks are successfully integrated within parametric modeling tools, others depend on the simplified modeling tools of the simulation software, or in some cases uses a text-based modeling. These types of models, known as “shoebox models”, don’t provide much flexibility to the designer as it is limited to simple forms of buildings and spaces.

Visualization of optimization results: It is very critical for the user to be able to interact with the optimization data in an informative way. Providing an efficient and clear way to visualize, sort and compare design results should be an integral part of the framework. However, most of the tools don’t provide any way to analyze or visualize the results, which forces the user to depend on other tools for the visualization and analysis of the results.

Guidance and knowledge-based system: Visualizing the results is usually not enough for inexperienced users. To provide a real decision support tool, a guidance system or knowledge-based support should be provided.

Chapter 4: Integrated Performance Optimization Framework

4.1 Simulation framework

From the literature study analyzed in chapter 3, several limitations for performing a holistic evaluation for building façade performance were highlighted. The framework presented in this chapter aims at overcoming some of these limitations by providing a parametric workflow that is capable of fulfilling integrative façade performance assessments as well as multi-objective optimizations. By relying on a parametric modeling software, the framework can be effectively used for the design of building façades with a high degree of complexity, from the simplest façade to geometrically complex designs.

4.2 Framework objectives

The framework aims at optimizing complex and multi-variant building façade models for the integrative environmental performance of the façade. The automated optimization process aims at reaching the highest performance in the aspects discussed in chapter 2: energy consumption, thermal comfort, visual comfort, daylighting, as well as minimizing the environmental impact and increase the possible energy generation.

4.3 Framework setup

Figure (4.3-1) shows the main structure and setup of the framework. The framework consists of three main phases: *parametric modeling*, *simulation,* and *optimization*. Within each of these phases, a group of components, inputs, and tools function in synergy to reach the optimized designs. The below sections describe each phase in more detail and the function of each component.

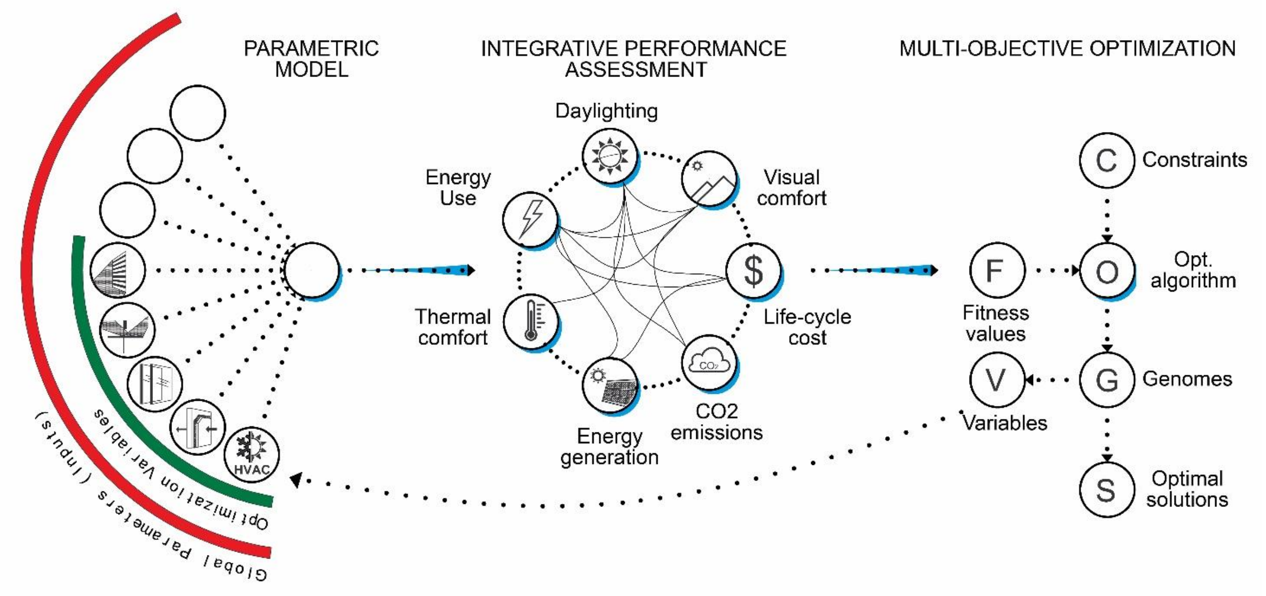

Figure 4.3-1

Illustration of the integrated simulation and optimization framework.

4.3.1 Parametric modeling and visual programming language

Models are abstract three-dimensional representations that aim to provide approximate imitations of the real world. (Papalambros and Wilde 2000).

Parametric modeling depends on mathematical formulas, rules, numbers and data values to create geometrical models. The models can be then morphed and controlled easily by changing the values rather than having to reconstruct the entire model. In architectural design, parametric modeling or parametricism is being used more often in the recent days and is considered an avant-garde architecture style in which all the elements of architecture have become parametrically malleable. (Schumacher 2008). Parametric design is based on exploration and iterative re-editing process. (Woodbury 2010). In that context, parametric design is distinctive than other methods of design and modeling in the fact of its capability to interact and respond to changes in design variables defined by the designer and the environment. According to Barrios (2005), the main unique characteristics of parametric design are:

- Offering more flexibility to design parts and assemblies of complex nature.
- Provide reliable systems to test instances of designs from a single model.
- Expand design exploration at the initial stages of the process.

As this research investigates the possibility of reaching optimal designs from a larger pool of design options, parametric modeling was chosen for its unique flexibility and efficiency when dealing with a vast number of options.

The developed framework for this research relies on the parametric modeling software Grasshopper[1] which is a Visual Programming Language (VPL) tool that is widely used by architects to create parametric designs and models.

In this research, parametric modeling was used to construct the main geometry and shape of buildings, but also to control other parameters or *inputs* such as building materials, building loads, simulations inputs, … etc. The primary model is defined with the use of *global variables* which includes general parameters e.g. project name, location (weather file), orientation, … etc., as well as building parameters e.g. space dimensions, shading devices, materials, … etc. The building parameters affect the building form or properties and can be used as optimization variables. As a result, the parametric model definition can generate a considerable number of design options according to the number and range of the design variables. However, it is the unique combination of design variables values that makes each design alternative distinctive.

Beside the *global variables* that define the design alternative, other *local variables* are used as inputs for the simulation or optimization software and control the accuracy and workflow of the simulations. A diagram for an example of a simple building zone using VPL and parametric modeling is shown in Figure (4.3-2).

In this research, several user components and parametric models with different complexity were prepared and tested in the next chapters. The user can use these models as ready-to-use templates or can create his own parametric model for higher flexibility and customization. The parametric model is then converted to different simulation models to adapt to the guidelines of the simulation types and software used.

[1] Grasshopper®: http://www.grasshopper3d.com/

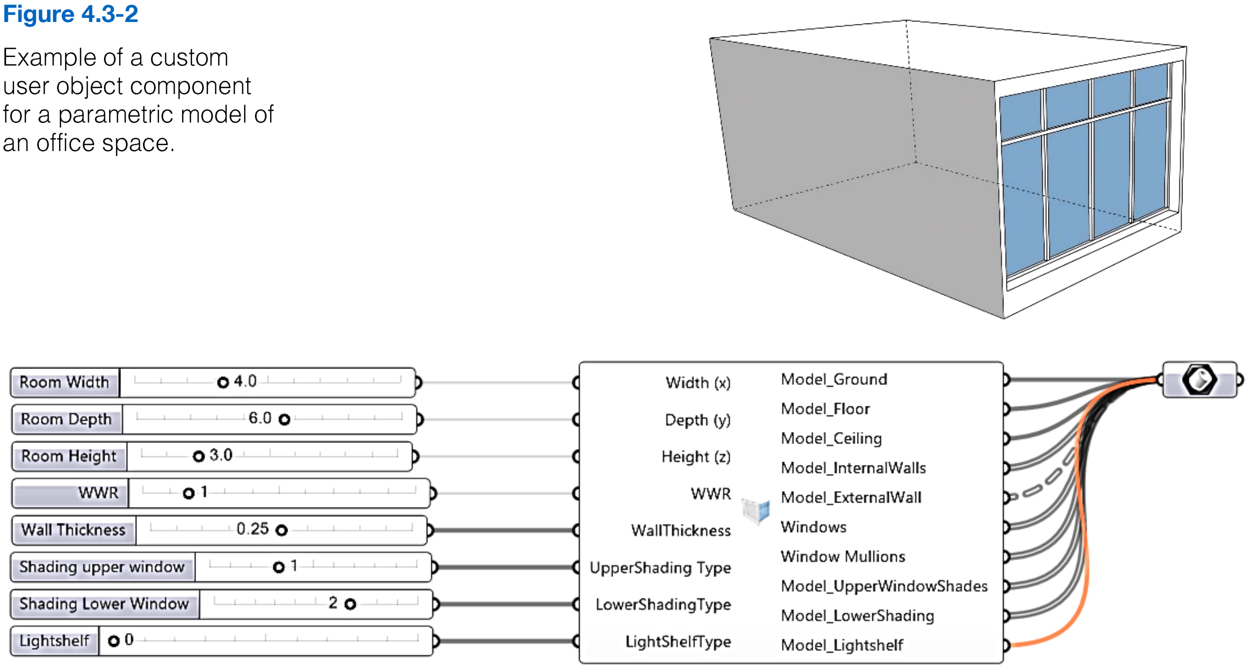

Figure 4.3-2

Example of a custom user object component for a parametric model of an office space.

4.3.2 Integrated performance simulation

In order to have a complete understanding of the façade's holistic performance, a number of simulations are conducted for each design option. The simulations use different metrics to provide detailed results on the annual energy consumption, daylighting performance, thermal comfort, visual comfort (glare and view), energy generation as well as life-cycle cost and life cycle assessment. The following sections discuss the simulation software packages used, the detailed input, outputs and metrics used and the relations and interoperability between the simulation tools.

Energy use

Minimizing the annual energy use is a major aspect of high-performance facades. The energy use for each design alternative was calculated hourly throughout the entire year for the cooling, heating, lighting and equipment loads. The Energy Use Intensity (EUI) was used to compare the efficiency of each design. For the energy simulations, Ladybug+Honeybee plugin (Roudsari and Pak 2013) was used as an interface to the simulation program EnergyPlus (US Dept. of Energy 2015). EnergyPlus is a validated whole building energy simulation engine developed by the United States Department of Energy. The parametric model is simplified and building materials and constructions are applied to the corresponding building elements to create the energy model.

User-defined inputs for the energy simulation include global inputs as well as local inputs such as:

Global inputs

- location (weather file)
- orientation
- energy model

Local inputs

- occupancy schedule
- equipment loads
- lighting power density
- HVAC cooling and heating set points

All surfaces of the tested spaces were assumed adiabatic, except the external wall with the glazing, to focus on the energy transfer from the studied facades. Lighting load schedules were obtained from the daylighting simulation and the occupancy and equipment load schedules were assumed to be daily from 8 AM to 6 PM with hour-saving time

For each design alternative, the simulation outputs include the cooling, heating, equipment and lighting loads. These are added later and divided by the space area to provide the annual Energy Use Intensity (EUI) in kWh/m^2/year. The simulation results also include the operative temperature, mean radiant temperature (MRT) and the relative humidity, which are used for thermal comfort calculation. Figure (4.3-3) shows a simplified diagram of the simulation process, inputs, and outputs.

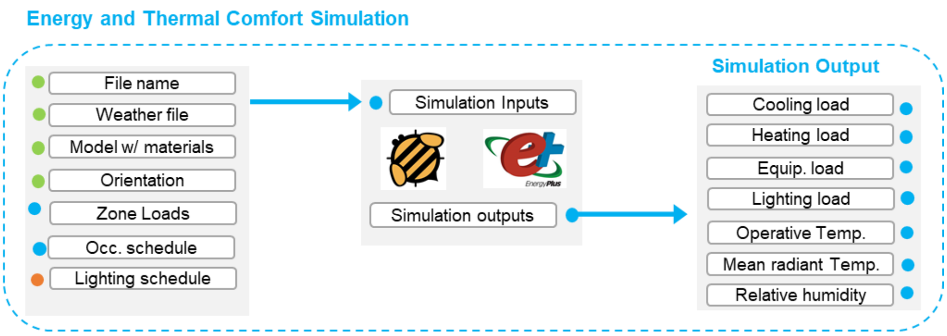

Figure 4.3-3

A simplified diagram of the energy and thermal comfort simulation process.

Thermal Comfort

Indoor thermal comfort was evaluated using the Predicted Mean Value and Predicted Percentage of Dissatisfied model (PMV-PPD). The PMV-PPD model is the most recognized model for thermal comfort and is based on a number of survey researches for air-conditioned spaces. It is also used by several standards such as ASHRAE Standard 55-2010 (Standard 55-2010), EN 15251 (CSN EN 15251), and the ISO 7730 standard (EVS-EN ISO 7730:2005).

The PMV index predicts the mean value of votes of a group of persons on a 7 points scale (Table 4.3-1). While the PPD index predicts the percentage of people that will be thermally dissatisfied.

Table 4.3-1

Seven points thermal sensation scale

+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

Both ASHRAE and ISO standards categorize the index values into three or four categories (Table 4.3-2). Since it's usually difficult to achieve category A while considering the accuracy of measurements, category B is usually used in real-world practice and is also the one used in this research.

Table 4.3-2

Categories of thermal environments

Category	Thermal state of the body as a whole	
	PPD %	PMV
A	<6	-0.2 < PMV< +0.2
B	<10	-0.5 < PMV< +0.5
C	<15	-0.7 < PMV< +0.7
D*	<25	-1.0 < PMV< +1.0

*only available in ASHRAE standard

As mentioned in Chapter 2, PMV and PPD depends on several parameters such as, *operative temperature*, *mean radiant temperature* and *relative humidity, air speed*, *metabolic rate* and *clothing level*. Both ASHRAE and ISO standards provide guidance and recommendations for each parameter. The PMV comfort calculator from the Ladybug+Honeybee plugin was used to calculate the PMV and PPD for each design alternative. The *operative temperature mean radiant temperature* and *relative humidity* were obtained from the energy simulation. Other inputs such as *air speed*, *metabolic rate* and *clothing level* could be adjusted by the user and were set to default values of 0.1m/s, 1 *mat,* and 1 *clo* respectively. Percentage of Discomfort Hours (PDH), which is the percentage of hours that had PPD more than 10%, was aimed to be minimized.

Daylighting

The quantity of daylighting present in a space can be quantified and measured using several methods. Static methods such as daylight factor and illuminance values can give a general idea of the daylighting performance and distribution in the space, and are still being used as general guidelines. Nonetheless, dynamic daylighting metrics such as spatial Daylight Autonomy (sDA), Daylight Availability (Dav) and Useful Daylight Index (UDI) provides more accurate information about the daylighting performance as they cover every hour in the year. However, it also requires a longer time for simulation.

In this framework, the effect of changing the variables on daylighting performance was measured using DIVA-for-Rhino (V 4.0)[2], a plugin for the 3D modeling software Rhino 3D[3]. Diva-for-Rhino is used to interface Radiance and Daysim for annual simulation and illuminance computation (Jakubiec and Reinhart 2011). Radiance is a daylighting simulation engine developed by Greg Ward and is known for accurate representation of daylight behavior. Radiance utilizes a raytracing algorithm to provide a realistic visualization of the space. (Larson and Shakespeare 2003)

Daylight performance was evaluated using the dynamic daylighting simulation which gives the results of several metrics. Most notably the IES spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) criteria which corresponds to the latest progress in daylighting simulation metrics introduced in the Illuminating Engineering Society standard IES LM-83-12 (IESNA, 2012). $sDA_{300Lux/50\%}$ was used to evaluate the presence of sufficient daylight by calculating the percentage of the floor area that receives 300 lux or more for at least 50% of the annual occupied hours. In this paper a sDA ≥ 50% was assumed to be acceptable. The annual sun exposure was used to describe the percentage of floor area that receives too much direct sunlight. ASE represents the percentage of the floor area that receives more than 1000 lux for at least 250 occupied hours per year. Occupancy schedule was assumed to be the same as the energy simulation. The calculations were made for a reference plane of 60

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2 DIVA-for-Rhino, an optimized daylighting and energy modeling plug-in for the Rhinoceros 3D modeling software. http://diva4rhino.com/
3 Rhinoceros. https://www.rhino3d.com/

measuring points in a grid of 0.6m* 0.6m, at a working-plane of 0.85 m height. Figure (4.3-4) shows a simplified diagram of the daylighting simulation.

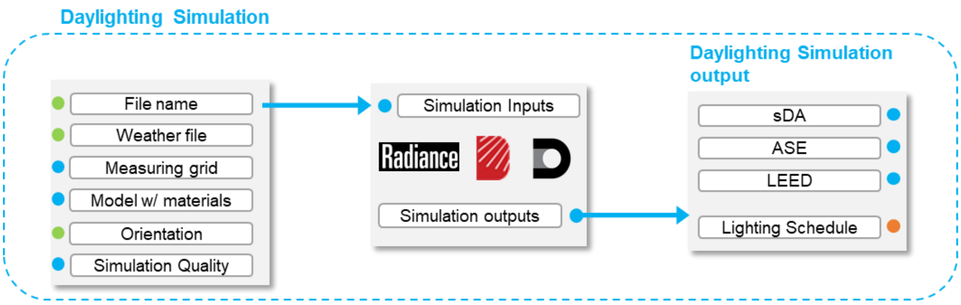


Figure 4.3-4

A simplified diagram of the daylighting simulation process.

Visual Comfort

In the framework, the visual comfort was calculated by combining the view factor and glare probability. For glare analysis Evaglare was used to measure the discomfort using the Daylight Glare Probability (DGP) index. The GDP was analyzed at 9:00, 12:00 and 15:00 on the solstice and equinox dates to cover the different sun positions. In the DGP index, glare is divided into four categories: intolerable glare (DGP > 45%), disturbing glare (45% > DGPP 40%), perceptible glare (40% > DGPP 35%), and imperceptible glare (DGP < 35%). For the view analysis, a view factor can be calculated using 2D or 3D isovist. Two- and three-dimensional isovists were created for the focal area of the viewer's field of view (Figure 4.3-5). The ratio between the number points seen from the vantage point in each case to a maximum number of possible points is calculated to compare between the different shading devices.

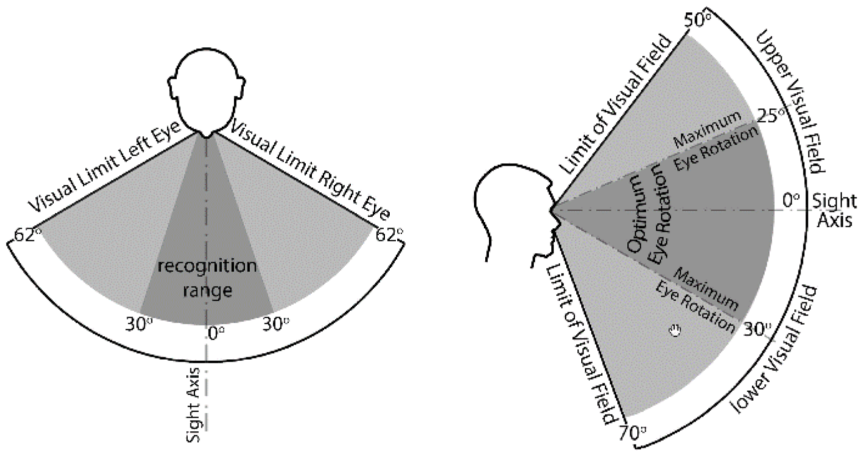


Figure 4.3-5

Diagram of the human cone of vision. showing the limit of the visual field and the area of recognition, in two directions, horizontally and vertically.

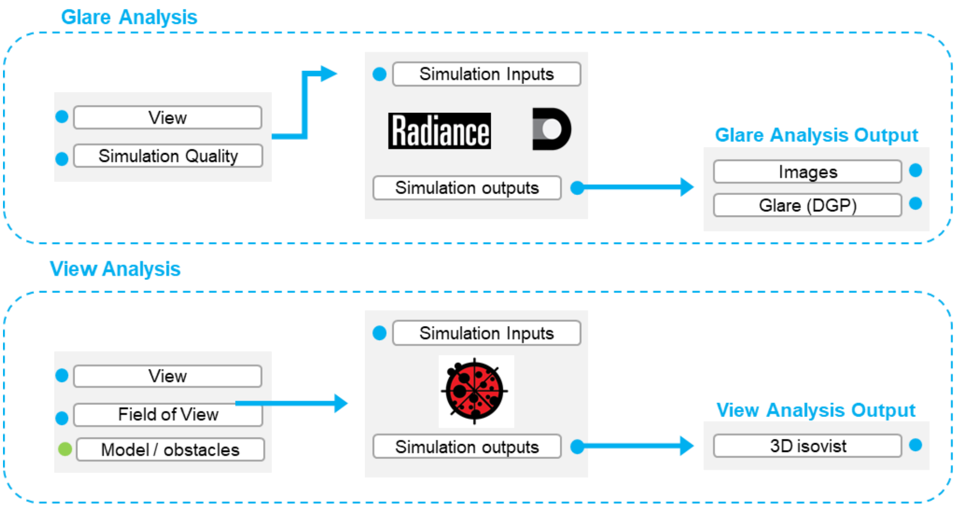


Figure 4.3-6

A simplified diagram of the visual comfort analysis process.

Energy Generation

The possibility for energy generation was calculated by assuming only solid surfaces of the façade are covered with Photovoltaics. The efficiency and real area covered can be controlled manually to resemble real life conditions. The PV simulation was made using Archsim, which is a part of the Diva-for-Rhino plugin. The plugin takes the panel geometry, panel efficiency and an effective area as inputs and then executes an EnergyPlus simulation to calculate the energy generated annually.

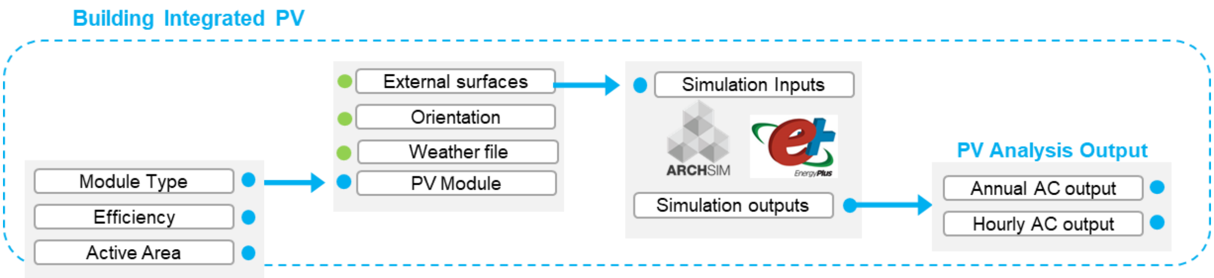


Figure 4.3-7

A simplified diagram of the energy generation simulation process

Life Cycle Assessment

Life Cycle Assessment was carried out using a parametric simplified method similar to that discussed in (Hollberg and Ruth 2016). The amount of materials from the façade elements is calculated from the parametric model. Information of the environmental impact and embodied energy of each material was compiled from the ÖKOBAUDAT and documented in a CSV file. A customized user component was then developed to extract this data and assign it to the corresponding material. Finally, the values of each indicator were added and presented per each m2 of the façade.

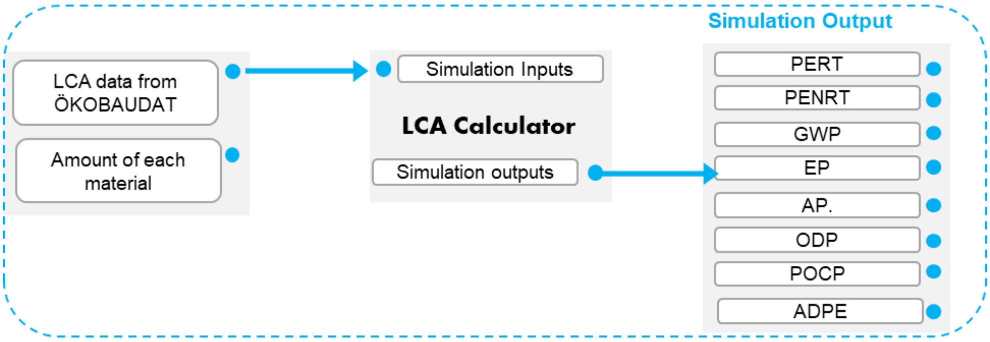


Figure 4.3-8

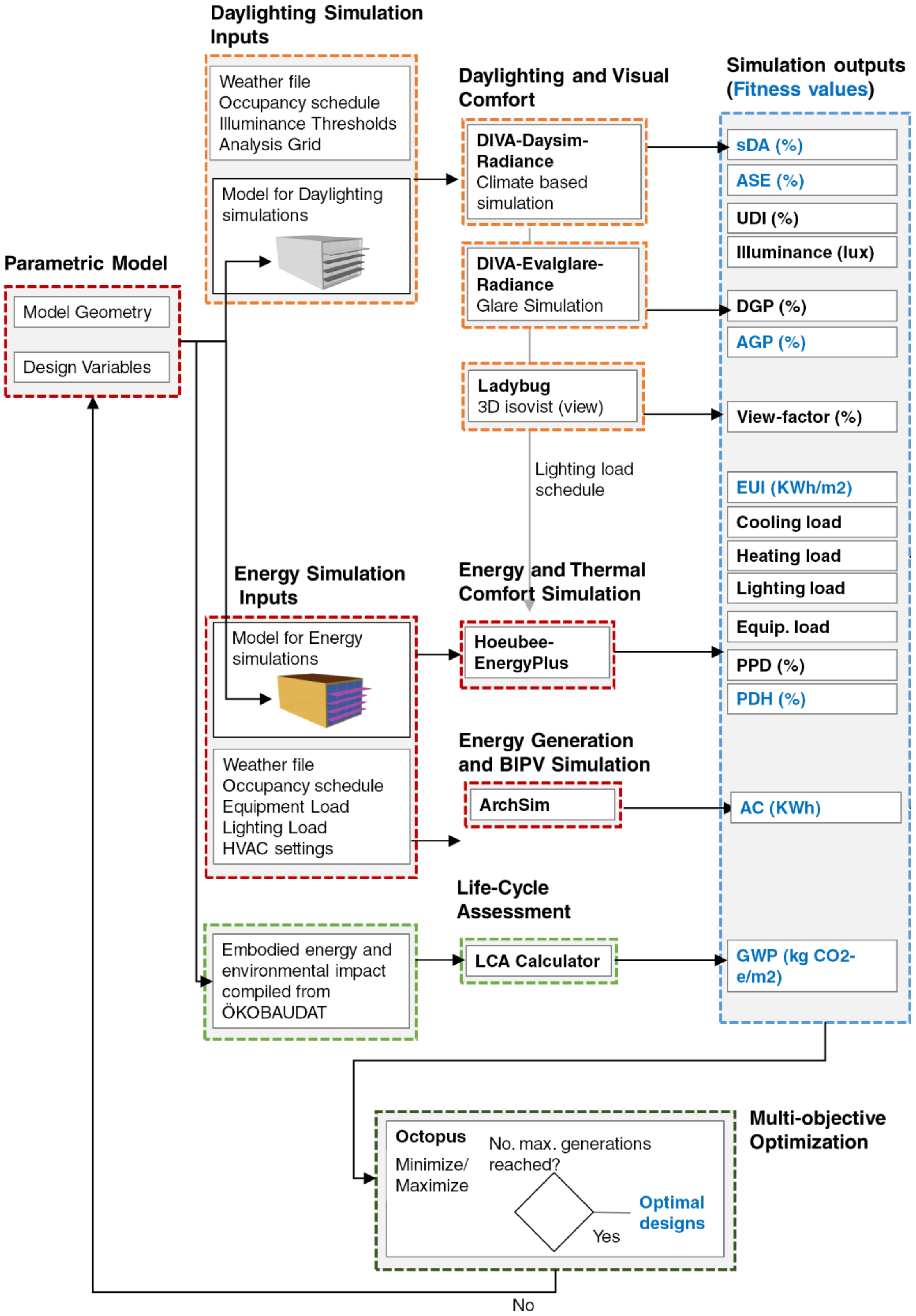
A simplified diagram of the life-cycle assessment analysis process.

4.3.3 Multi-objective optimization

Multi-objective optimization was performed using the Grasshopper's plug-in Octopus (Vierlinger, R., & Hofmann, A. 2013). It is based on the Evolutionary algorithm SPEA-2 developed at ETH Zurich (Zitzler, E., et al. 2001) and applies evolutionary principles to provide Pareto-optimal solutions. A solution is considered a Pareto-optimal if no other solution exists that "would decrease some criterion without causing a simultaneous increase in at least one other criterion (assuming minimization)" (Coello C. et al. 2006). In other words, Pareto-optimal solutions are non-dominant solutions that are considered as equal solutions. A trade-off between the objectives is therefore essential to judge them. Annual Sunlight Exposure was used as a Boolean objective, so that only cases that achieved ASE less than 10% were considered in the optimization. Optimization was performed for the previously mentioned variables and three objective functions were used: the sDA, EUI and PDH. For each of the two studied locations, the optimization process continued for 10 generations with a population size of 30. Mutation rate was set as 0.5, mutation probability as 0.1 and crossover as 0.8. The optimization workflow is shown in figure (4.3-9). Results were then exported to Excel and analyzed using the web-based application "Pollination" to create parallel coordinates graphs (Pollination, 2015).

Figure 4.3-9

A conceptual diagram of the integrative performance optimization framework



Chapter 5: Case Studies

5.1 Introduction

The aim of this chapter is to examine the usefulness and effectivity of the framework in helping designers in arriving at high-performance façade designs. Two case studies were conducted following similar approaches, but with different objectives. In the first case, the framework was used for a design problem with opposing objectives. The aim, in this case, was to examine the trade-off between the two objectives and look for solutions that provide acceptable performances for both objectives. In the second case, a more complicated case was examined with the objective of examining the frameworks ability to act as a design explorer tool. In that case, the framework was introduced to a multi-variant, multi-objective design problem, and used GA optimization to reach a set of optimal solutions.

5.2 Case study 1: optimization of facade design for daylighting and view- to-outside: A case study in Lecco, Lombardy, Italy. [4]

In this case study, the ability of the Integrative Performance Optimization (IPO) framework to aid in design problems with contradicting objectives was investigated. The case study is based on the result of an evidence-based designed building project that was developed for the Sustainable Building Technologies (SBT) course and studio of Architecture Design (AD) in the Polytechnic University of Milan, Lecco campus. The design project was for a multi-functional building located in La Piccola area, in the historical industrial-area of Lecco city, in Lombardy, north of Italy. (Wageh et al. 2016)

[4] Part of this thesis section was published in Gadelhak, M., & Wageh, M. A. (2017). Optimization of Facade Design for Daylighting and Viewto-Outside: A case study in Lecco, Lombardy, Italy. In A. Fioravanti, S. Cursi, S. Elahmar, S. Gargaro, G. Loffreda, G. Novembri, & A. Trento (Eds.), ShoCK! - Sharing Computational Knowledge! - Proceedings of the 35th eCAADe Conference, 20-22 September 2017 (Vol. 1, pp. 229-236). Sapienza University of Rome, Rome, Italy.

The building's site is located directly in front of the new campus of the Polytechnic University of Milan and has an unobstructed panoramic view of the surrounding mountains due to the absence of tall buildings around it. The proposed design consisted of three floors plus a ground floor with various functions related to the university. The fourth floor which will be studied in this section is dedicated to an open-plan workshop space with 150 m2 area. In order to provide a 360° panoramic view of the surrounding mountains, the fourth floor has floor-to-ceiling windows in all four orientations which left the space, however, vulnerable to direct sun penetration. (Figure 5.2-1).

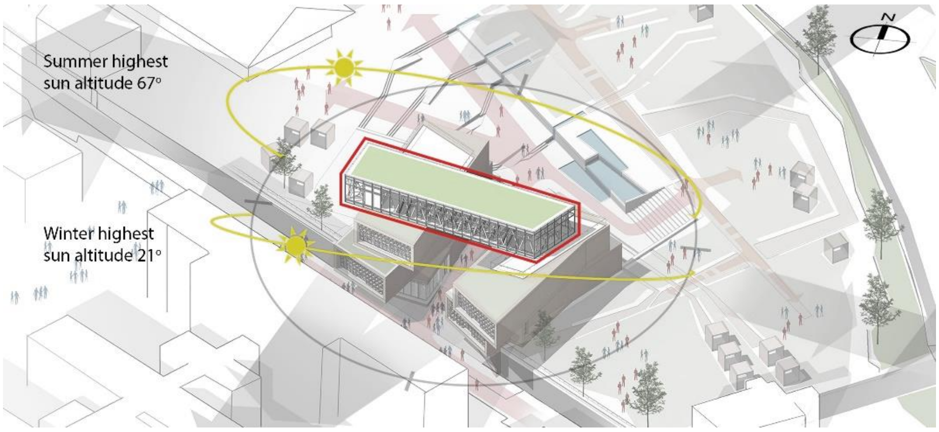


Figure 5.2-1

Project location and building configurations in the site. The diagram shows the orientation of the fourth floor with the sun altitude

Because of having fully glazed facades, the biggest challenge facing the proposed project was to provide indoor visual comfort and avoid the occurrence of glare as much as possible while maintaining the view from inside to outside with minimum obstruction. The four façades, especially the south, overlooks the best landscapes of the city of Lecco since it looks directly on Lecco's mountains. Hence, the importance of keeping the 360° panoramic view unobstructed while providing enough daylight for the workshop space.

5.2.1 Climate condition

The city of Lecco has a humid subtropical climate, with hot and humid summer and cold winter. The highest sun altitude is 20.8° in winter and 67.4° in summer. Annual global radiation can rise to 1600 kWh/m2 per year. The temperature rarely goes far below zero Celsius, the winter conditions nonetheless require non-negligible heating systems for the comfort. On the other hand, in summer, the high humidity and temperatures (often rising over 25° Celsius from June to August) require an equally important cooling load. As the air flow rate through the year is not adequate to provide natural ventilation, special attention for cooling and heating loads is necessary. Figures (5.2-2, 5.2-3, and 5.2-4) show the daily temperature, monthly radiation and hours of sunshine through the year.

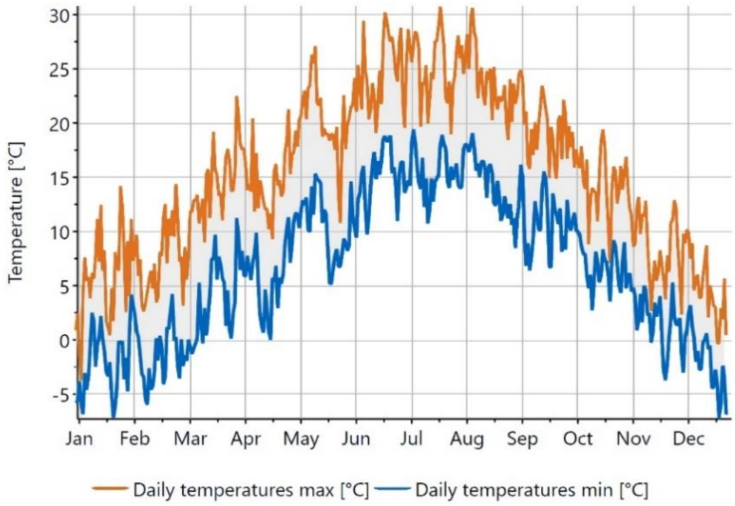


Figure 5.2-2

Daily temperature
Lecco, Italy
Source: METEONORM:
www.meteonorm.com

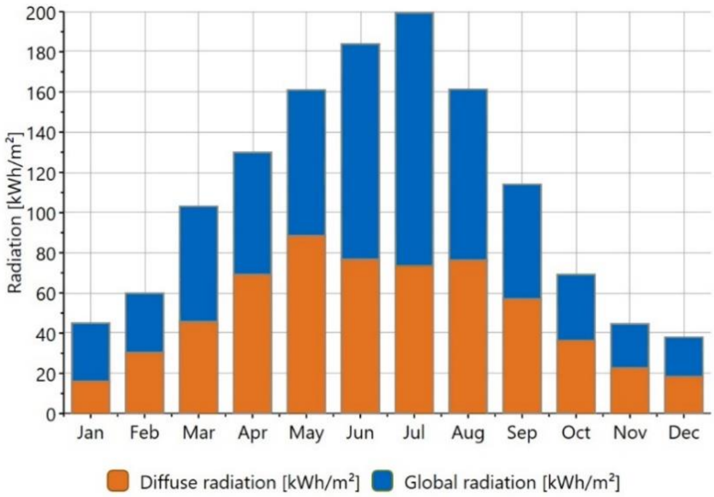


Figure 5.2-3

Radiation chart
Lecco, Italy
Source: METEONORM:
www.meteonorm.com

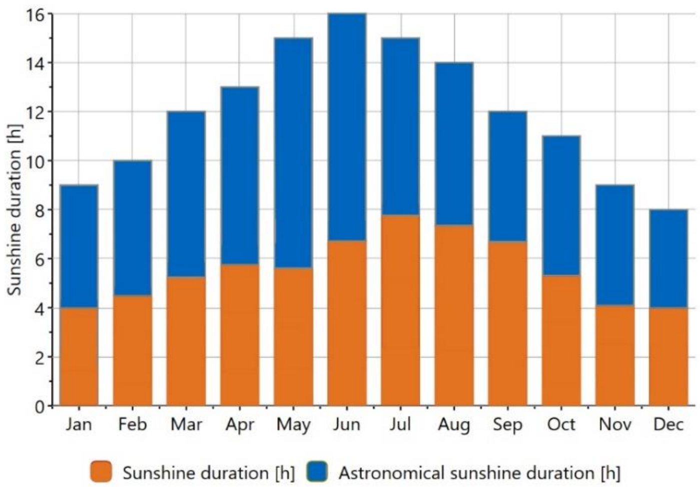


Figure 5.2-4

Monthly average
sunshine duration
Lecco, Italy
Source: METEONORM:
www.meteonorm.com

5.2.2 Space description

The studied space has a rectangular shape with the longer sides having a north-south axis with a tilted angle of 10°, and the short sides facing east and west. While the north façade is not affected by high sun exposure, the south façade is subject to high exposure for most of the day, throughout the year. East and west facades had a small impact on the daylighting performance of the space due to their relatively small area and being separated than the working space by the staircase and elevators cores. The architecture plan of the studied space is shown in figure (5.2-5).

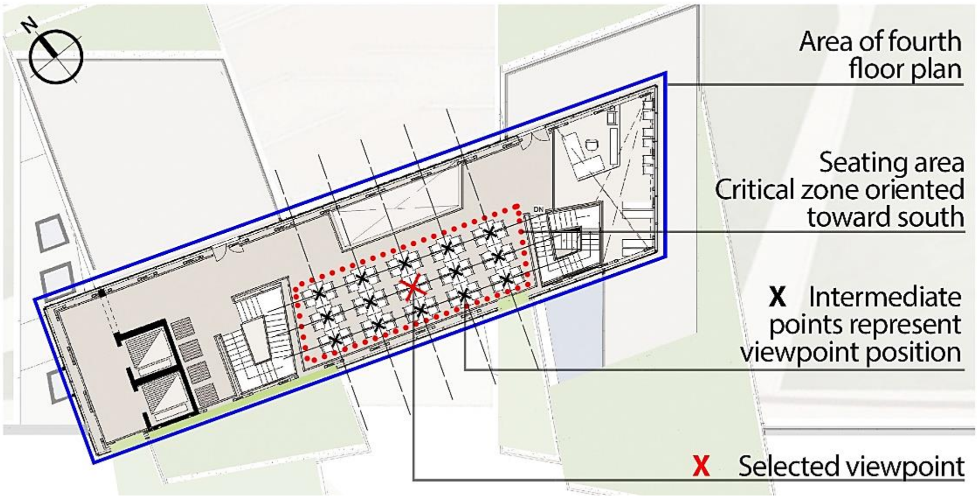


Figure 5.2-5

Architecture plan for the forth-floor. The seating area facing the south façade has the most sun penetration and therefore was selected for the analysis.

5.2.3 Design approach

Conventional design methods of passive techniques, such as shading devices like horizontal shades, venetian blinds and screens, were historically used especially in south facades to reduce the sun exposure, provide adequate daylight and to reduce the glare probability. Several research works investigated the characteristics of shading devices on daylighting as well as energy performance (Kirimtat et al. 2016). The concerns in using this kind of shading device are that it doesn't implicate the view-to-outside factor as a driving force for the design (Gadelhak and Wageh 2017). Therefore, a trade-off between the different measures has to be reached in order to achieve a visual comfort and preserve the view of the surrounding alpine landscape. In this case study, the IPO framework was used to improve the visual comfort of the users by studying relation between the two parameters (daylight and view) by applying daylighting and glare analysis as well as view assessment of different shading devices.

5.2.4 Methodology

The IPO framework was used to model and simulate the space for daylighting, glare and view to the outside. The aim was to find design solution that can achieve good daylighting performance without sacrificing much of the view.

Modeling

A parametric model for the multi-functional building was created using Grasshopper. The investigated space had the dimensions of 7.5 m x 20.0m with 3.3m ceiling height. Different types of shading devices were investigated for the daylighting performance, glare probability and view to outdoors. The performance of five shading devices was examined: horizontal shading, vertical shading, egg crate, an external diagrid structure, and an external diagrid structure with an overhang. For each of these shading devices, the impact of changing the vertical (or horizontal) shading angle was studied. The impact of changing the eggcrate thickness and spacing for the diagrid was also considered. Figure (5.2-6) shows an illustration of the five shading devices and their design parameters. Seven different cases for each of the horizontal and vertical shadings were studied and 35 cases for each of the other three shading devices. Overall 119 shading designs were examined. The range of the parameters for the shading devices that were examined are shown in table (5.2-1).

Figure 5.2-6

The five studied shading systems and its design parameters.

A. Vertical louvres.
B. Horizontal louvres.
C. Eggcrate.
D. Diagrid louvres.
E. Diagrid with overhang.

For each, the most effective variables were identified. Which include:
- modular size
- shading angle
- shading thickness

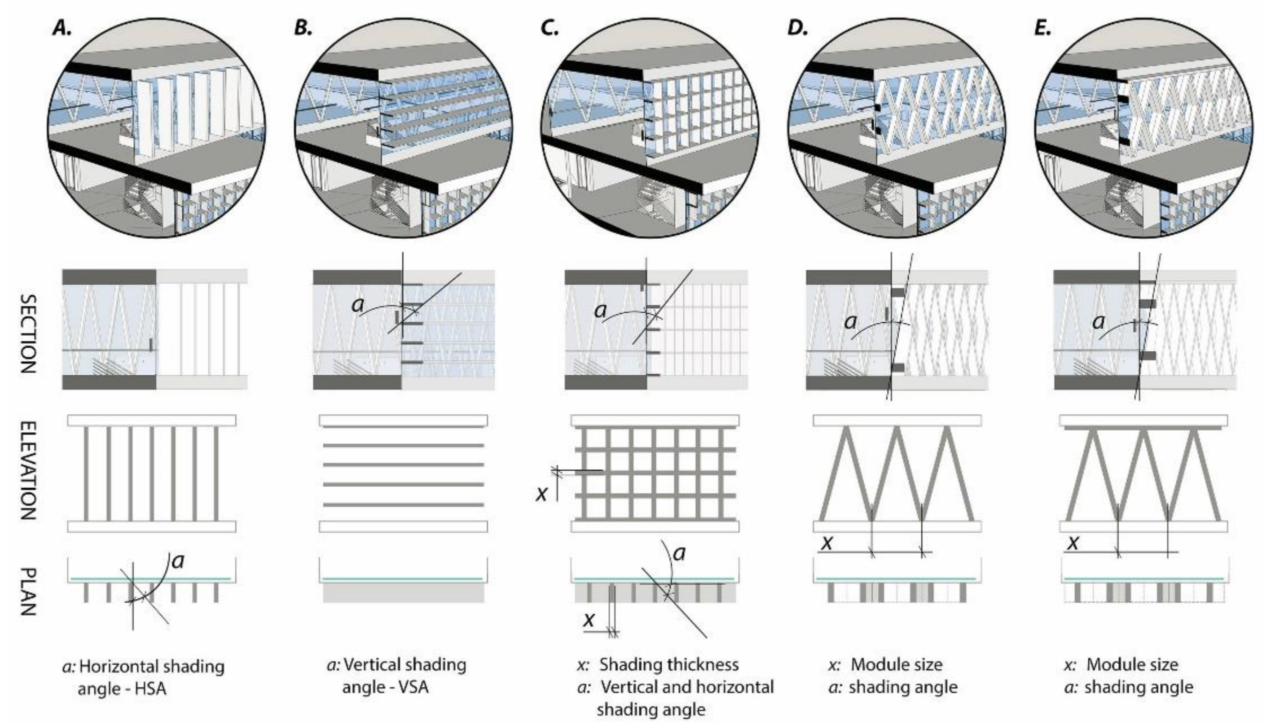


Table 5.2-1

Design parameters of the studied shading devices.

Shading type	Parameters	Range
Horizontal shading	Vertical Shading Angle (VSA)	20° to 50° with a step of 5°
Vertical shading	Horizontal Shading Angle (HSA)	20° to 50° with a step of 5°
Eggcrate	Vertical Shading Angle (VSA)	20° to 50° with a step of 5°
	Thickness	2.5 to 12.5 cm with a step of 2.5 cm
Diagrid structure	Vertical Shading Angle (VSA)	20° to 50° with a step of 5°
	Number of Modules (Spacings)	6, 12, 18, 24 and 30 Modules
Diagrid structure + overhang	Vertical Shading Angle (VSA)	20° to 50° with a step of 5°
	Number of Modules (Spacings)	6, 12, 18, 24 and 30 Modules

Simulation

Daylighting analysis was carried out using DIVA for Rhino. Daylight availability was chosen as the evaluation metric, which was found more suitable for the studied case. The measuring nodes are divided according to three criteria, daylit for points that receives illuminance between 300-3000 lux for 50% of the time, over lit for points that receives >3000 lux for at least 10% of the time, and partially daylit for points that has illuminance values<300 lux for more than 50% of the time. The aim is, therefore, to increase the daylit area of the space. The analysis grid had a desk-level height of 0.80 m and spacing of 0.60 m.

Glare and view analysis were conducted for a selective viewpoint that represents a seated person (height = 1.2m), positioned at a distance of 2.0m from the facade and facing the window. For glare analysis Evaglare was used to measure the discomfort using the Daylight Glare Probability (DGP) index. The DGP was analyzed at 9:00, 12:00 and 15:00 on the solstice and equinox dates to cover the different sun positions. In the DGP index, glare is divided into four categories: intolerable glare (DGP > 45%), disturbing glare (45% > DGP 40%), perceptible glare (40% > DGP 35%), and imperceptible glare (DGP < 35%). In this study, each category was given a score number with imperceptible glare having the highest score (3 pts) and intolerable glare the least (0 pts). The Annual Glare Percentage (AGP) is then calculated to compare the performance of different shading designs, where

AGP = 0% means that only imperceptible glare occurs at all times and the AGP = 100% indicates that an intolerable glare can be witnessed at all times. For the view analysis, a view factor was calculated using 3D isovist by generating a number of rays from a vantage point in the direction of the viewing windows. The ratio between the number of rays obstructed by the shading device to the total number of rays is used to compare between the different shading devices. In this study, the vantage point is the same one defined for the glare analysis.

The results from the three analysis criteria, daylighting performance (DAv), Glare (AGP), and View Factor are compared to arrive at shading devices with a satisfactory performance. Acceptable values for the three criteria were assumed to be 75%, 50% and 50% for the daylight availability, accumulated glare percentage, and view factor respectively.

Optimization

Since the number of the tested cases in this study was relatively low, a brute force optimization method was used. Which means that all the 117 cases were simulated for the three criteria and no selective algorithms were used.

5.2.5 Results

Base case results

The unshaded facade was assumed as the base case in this study in order to evaluate the effect of each shading device on the daylighting, glare and view performance. The base case had a low daylighting and glare performance due to the vast area of unshaded glazing in all its four facades. Because of the penetration of direct sunlight, the daylit area reached only 36%, while the overlit area occupied almost two-thirds of the space. Figure (5.2-7) shows the daylighting availability results for the base case.

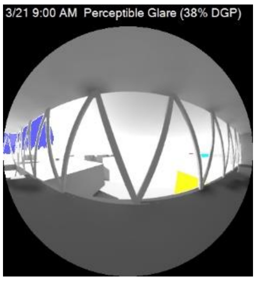
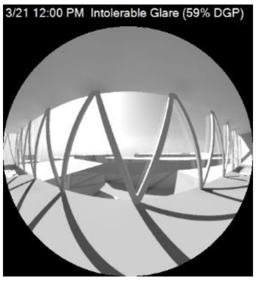
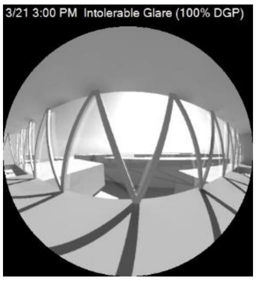
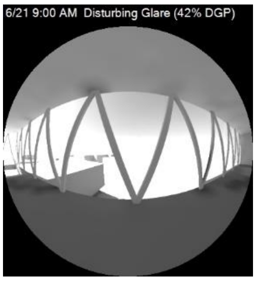
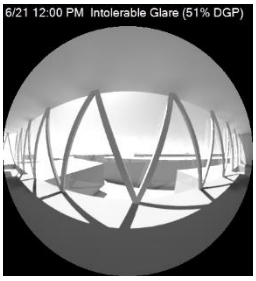
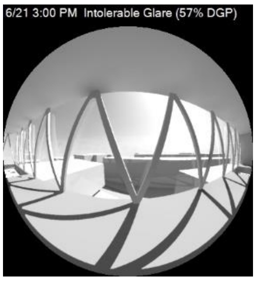
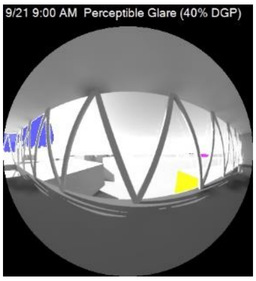
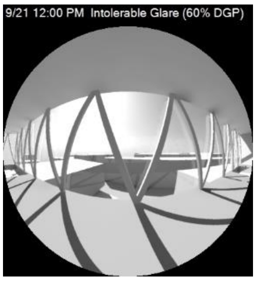
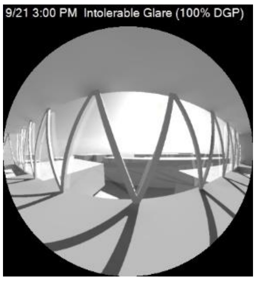
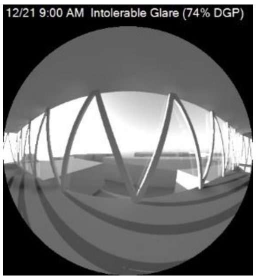
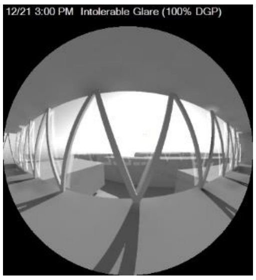
Figure 5.2-7

Daylight availability distribution in the base case

The annual glare score was found to be very low with a value of 13% as an intolerable glare was witnessed in most of the times with the exception of the morning hours. however, even during morning hours, a perceptible or disturbing glare was witnessed. The base case has, however, a panoramic view with only the internal structure as a physical obstacle. Table (5.2-2) shows the glare analysis results for the base case.

Table 5.2-2

Glare analysis results for the base case

	At 9:00 AM	At 12:00 PM	At 3:00 PM
21/3			
21/6			
21/9			
21/12			

Horizontal and vertical shadings

The horizontal shading devices had a significant effect on the daylighting performance, as most of the cases had better performance with over 90% daylit area percentage, in comparison to just 36% in the base case. The glare analysis, however, showed a high probability of glare occurrence and only one case achieved an AGP lower than 50%. The impact on the view was, however, better than anticipated with only between 17% to 27% of the view obstructed. Cases with larger extrusions (higher shading angles) had a better daylighting and glare performance while cases with smaller extrusions had a better view factor. (Figure 5.2-8).

In contrary, vertical shadings provided a poor but mostly acceptable daylighting performance. The daylit area percentages ranged between 49% with a Horizontal shading angle = 20°, and 60% with HAS=50°. Glare analysis also showed a high probability of glare occurrence all year round with a maximum annual score percentage of 64%. Nevertheless, the view factor was also found acceptable in all the cases with a maximum view factor of 87% and a minimum of 64%. (Figure 5.2-9).

Eggcrate

Thirty-five cases of eggcrate shadings were analyzed. Almost all the cases achieved over 80% daylit area and half of the cases reached 100% daylit area. Moreover, unlike the horizontal and vertical shading, the eggcrate reduced the chance of glare occurrence significantly. Most of the cases had an acceptable annual glare percentage and, in few cases, the AGP reached less than 20%. This, however, came in the expanse of the view performance. With the eggcrate cells causing a significant obstruction to the view, the view factor was found to be unacceptable in most of the cases. Only cases with very small thickness (high perforation ratio) and small extrusion achieved acceptable view factor. However, in these cases, the glare performance was at its lowest values and was below the acceptance threshold. Only one case achieved an acceptable performance in all the three criteria which had a thickness of 2.5 cm and 35° shading angle. Figure (5.2-10) show the daylighting, glare and view performance for eggcrate shadings with 7.5 cm thickness and different shading angles.

Figure 5.2-8

The effect of changing the shading angle on the daylighting, glare, and view performances for horizontal shadings.

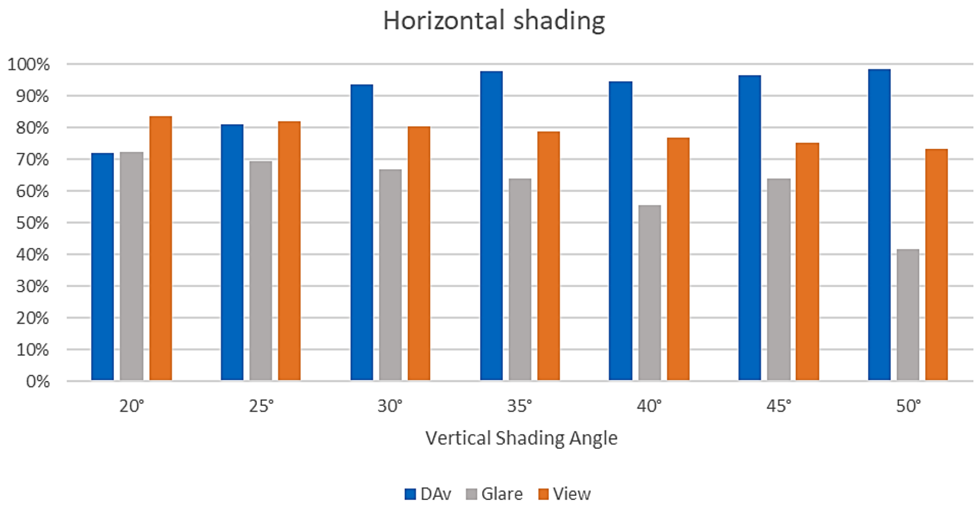


Figure 5.2-9

The effect of changing the shading angle on the daylighting, glare, and view performances for vertical shadings

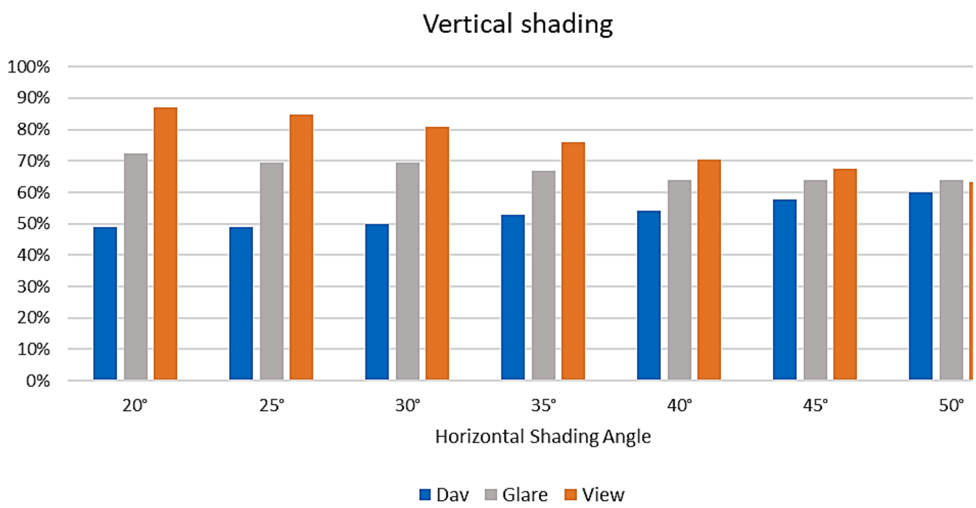
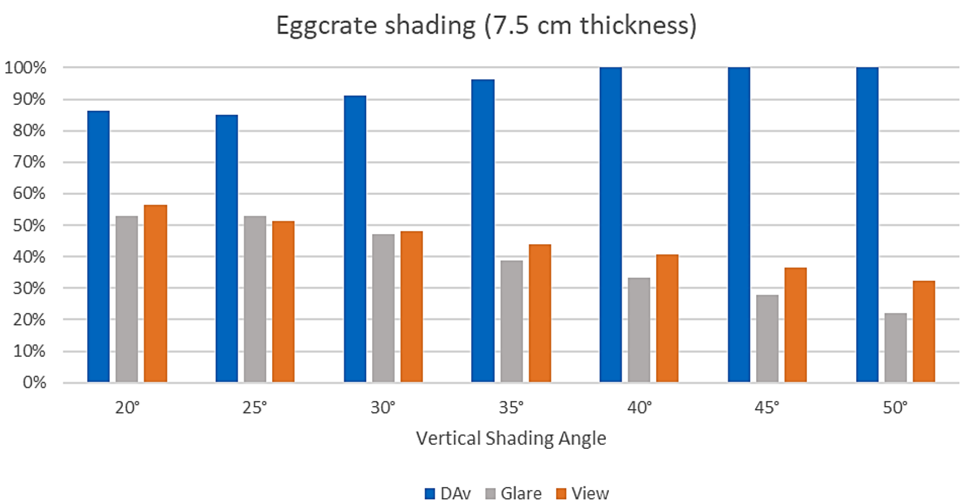


Figure 5.2-10

The effect of changing the shading angle on the daylighting, glare, and view performances for eggcrate shading with 7.5 cm thickness.



Diagrid structure

All the 35 cases of the external diagrid structure had a good impact on the daylight performance with a minimum daylit area percentage of 76% and nearly half of the cases with 100% daylit area. Similar to the eggcrate, the diagrid structure also enhanced the visual comfort significantly as the glare probability decreased and the AGP reached 0% in several cases. The external view also showed satisfactory performance with a maximum of 85.54% and most of the cases with view factor higher than 50%. Nine different cases achieved a satisfactory performance in all three areas of analysis. Figure (5.2-11) shows the effect of changing the shading angle on a diagrid shading with 18 modules.

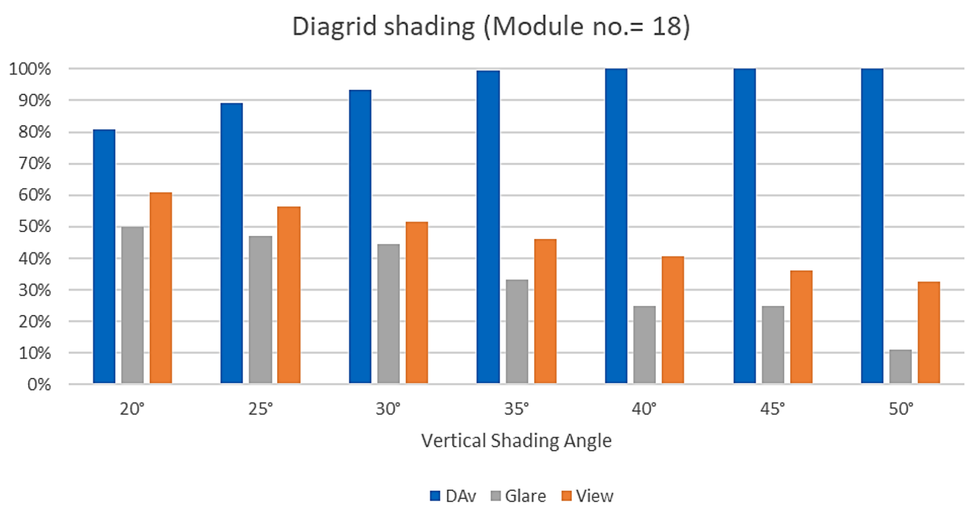


Figure 5.2-11

The effect of changing the shading angle on the daylighting, glare, and view performances for a diagrid shading with 18 modules.

Diagrid with overhang

This unique shading solution aimed at combining the positive impact of both horizontal and diagonal shading devices. Once more, 35 different configurations were tested. It succeeded in achieving notable improvements in all of the three criteria. Daylighting performance achieved more than 90% daylit area in all cases with most cases having a 100% daylit area percentage. Glare probability also improved as almost all of the cases had an acceptable performance and AGP reaching 0% in several cases. While not all the cases had a satisfactory view performance, in many cases the view factor had an acceptable value and reached a maximum of 86%. In many cases, the daylighting, glare and view were found to have acceptable and significantly improved performances. One notable case was with 45° shading angles and 6 modules of diagrid external structure, where daylit area percentage reached 100%, AGP of 25% and view factor of 71%.

Overall 14 different configurations achieved an acceptable performance in all the three criteria.

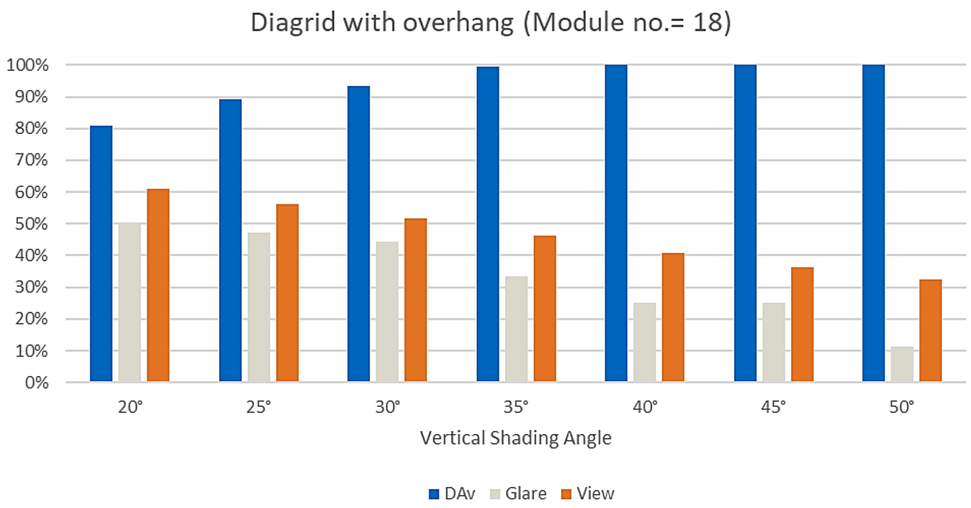


Figure 5.2-12

The effect of changing the shading angle on the daylighting, glare, and view performances for a diagrid with overhang shading system with 18 modules.

5.2.6 Discussion and conclusion

In this case study, the IPO framework was used as a support tool for designing building facades that overlook exceptional scenery and views, which requires particular care not to obstruct the view to the outdoors. Nevertheless, poor shading design can usually result in high solar penetration and glare probability affecting the ability of the users to enjoy the outdoor view. In this study, 119 different configurations of five shading systems were investigated. Overall, 25 different configurations from 4 systems of the shading devices achieved a satisfactory performance for daylighting, view and glare. The combined shading of an external diagrid structure and a horizontal overhang offered the best performance with 14 cases, followed by the diagrid shading and eggcrate and finally the horizontal shadings where only one case achieved an acceptable performance. Figure (5.2-13) shows the performance results in the three areas, daylighting, glare and view for the three most effective systems. The cases with acceptable performance are highlighted. The effect of the different shading systems on glare performance is presented in table (5.2-3).

Figure 5.2-13

Daylighting, glare, and view performances for the Eggcrate, Diagrid, and diagrid with overhang shadings. The cases with satisfactory performances are highlighted.

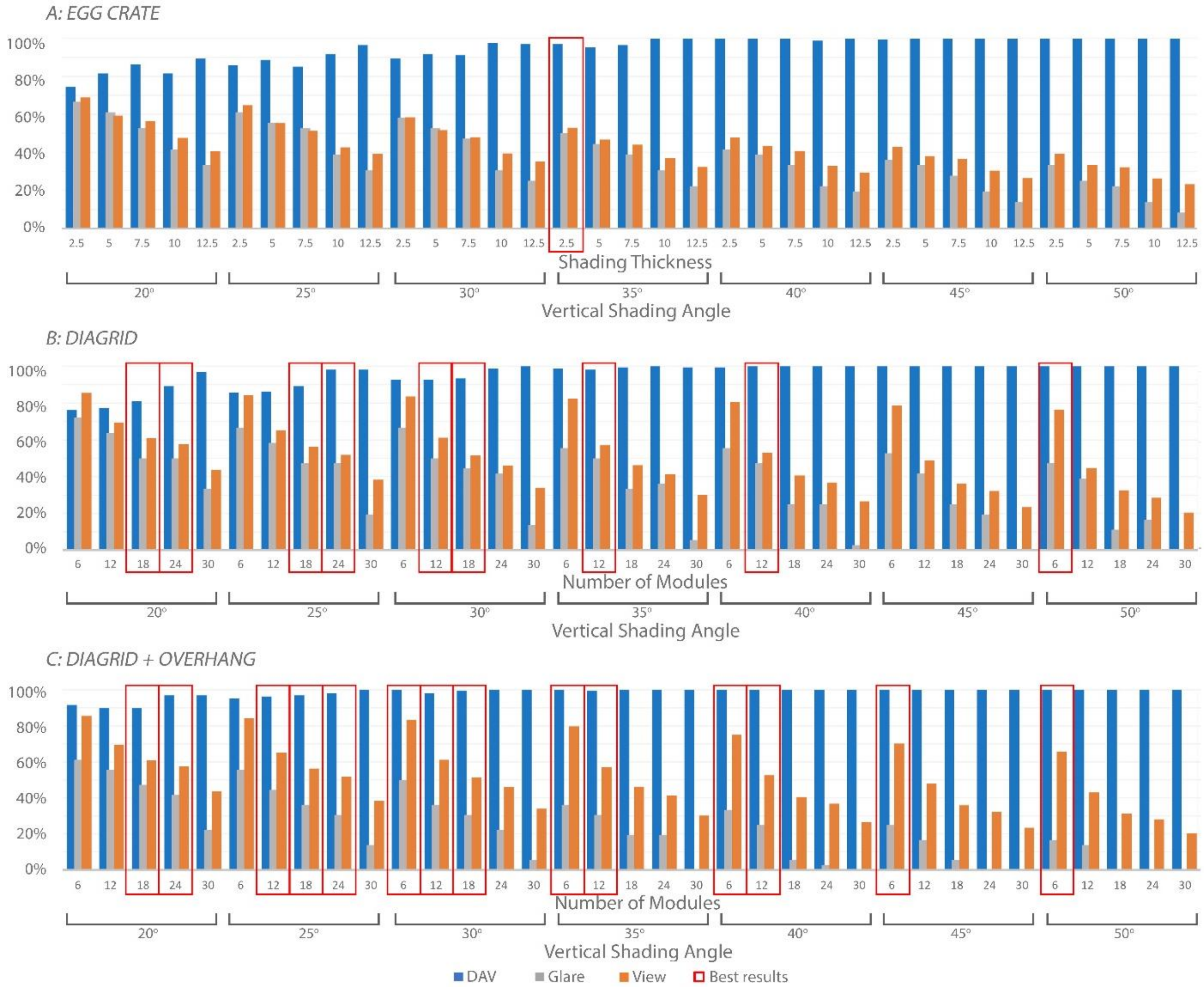
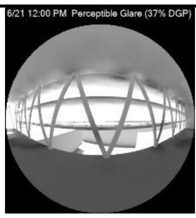
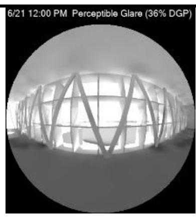
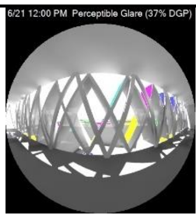
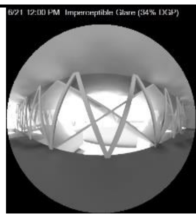


Table 5.2-3

Glare performance at 12:00 on 21 June for the base case and four different shading configurations

Shading system	Base Case	Horizontal shadings	Eggcrate	Diagrid	Diagrid and overhang
Glare	 **51% DGP**	 **37% DGP**	 **36% DGP**	 **37% DGP**	 **34% DGP**
Parameters	*No shading system*	*VSA = 50°*	*Shading thickness = 2,5 cm; VSA = 35°*	*No. of modules= 18; VSA = 30°*	*No. of modules= 6; VSA = 45°*

5.3 Case Study 2: optimization of office building façade to enhance daylighting, thermal comfort, and energy use intensity: A case study of a reference office space in Cairo and Munich.[5]

In the second case study, the framework is examined for a wider and more integrative design problem. An office building façade was optimized for the integrated performance of total energy consumption, daylight quality, and thermal comfort. Given the larger number of objectives and also variables this case study aims to investigate the practicality of using the IPO framework as a design exploration tool, in other words, how far would the framework be able in delivering useful design information and finding optimal solutions from a large set of design alternatives?

5.3.1 Climate conditions

The investigated office space was studied for two climates, the hot and dry climate of Cairo, Egypt and cooler the more humid climate of Munich, Germany. Cairo has a hot desert climate, with the high temperature rises to 40° during summer months and ranges between 14° to 22° during the winter season. With more than 3,400 sunshine hours/year and annual solar radiation equivalent to 2,600 kWh/m2, Cairo has a generous global solar radiation especially in summer with a clear sky and a very limited cloud coverage. (Figures 5.3-1:5.3-3). Munich, on the other hand, has an all-year humid climate with cold winter and warm summer (Kottek et al. 2006; Rubel et al. 2017). Average high and low temperatures change significantly during the year. High temperature rarely goes above 30° in summer (July) while the low temperature remains below zero degrees for most of the coolest month (January). Solar radiation and sunshine hours are of course limited when compares to Cairo with nearly 1,800 days of sunshine and 1200 kWh/m2 annual solar radiation. (Figures 5.3-4:5.3-6).

[5] Part of this thesis section was published in Gadelhak, M., & Lang, W. (2016). Optimization of Office Building Façade to Enhance Daylighting, Thermal Comfort and Energy Use Intensity. In N. Hamza & C. Underwood (Eds.), Proceedings of the 3rd IBPSA-England Conference BSO 2016, Newcastle, 12th-14th September 2016.

Figure 5.3-1

Daily temperature
Cairo, Egypt
Source: METEONORM:
www.meteonorm.com

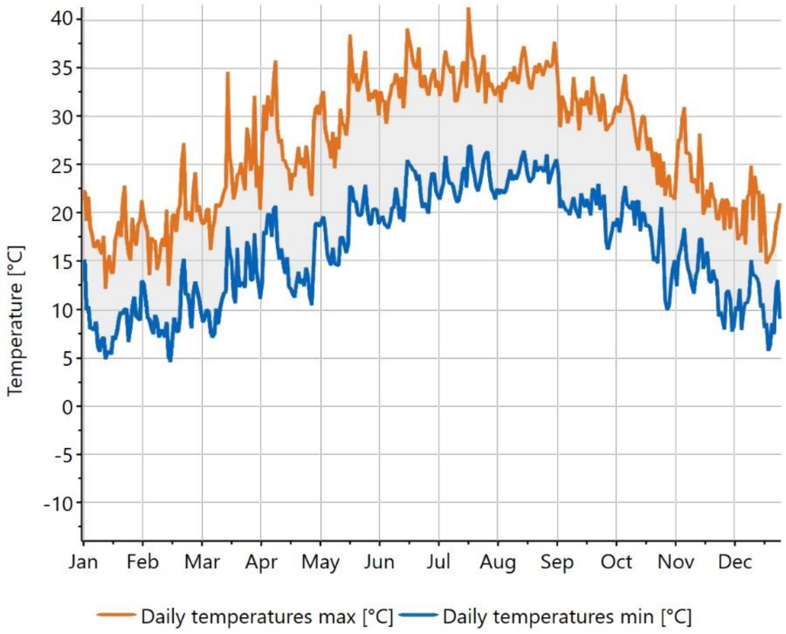


Figure 5.3-2

Radiation chart
Cairo, Egypt
Source: METEONORM:
www.meteonorm.com

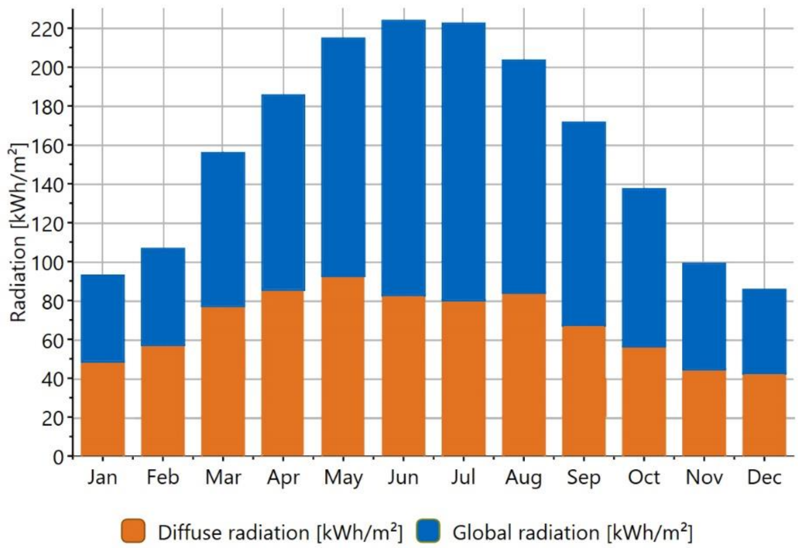
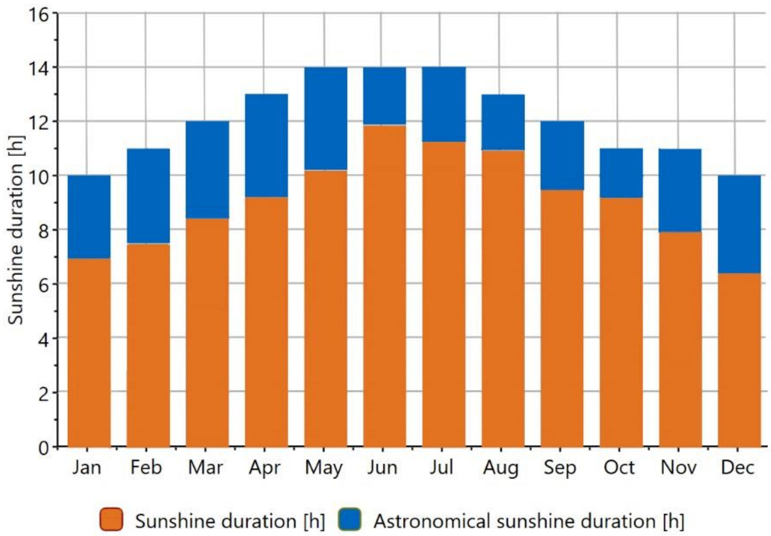


Figure 5.3-3

Cairo, Egypt
Source: METEONORM:
www.meteonorm.com



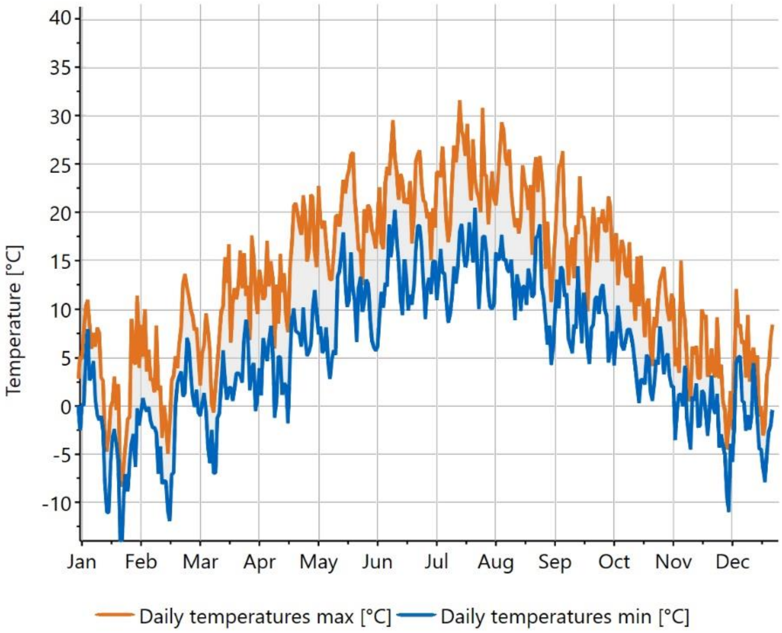


Figure 5.3-4

Daily temperature
Munich, Germany
Source: METEONORM:
www.meteonorm.com

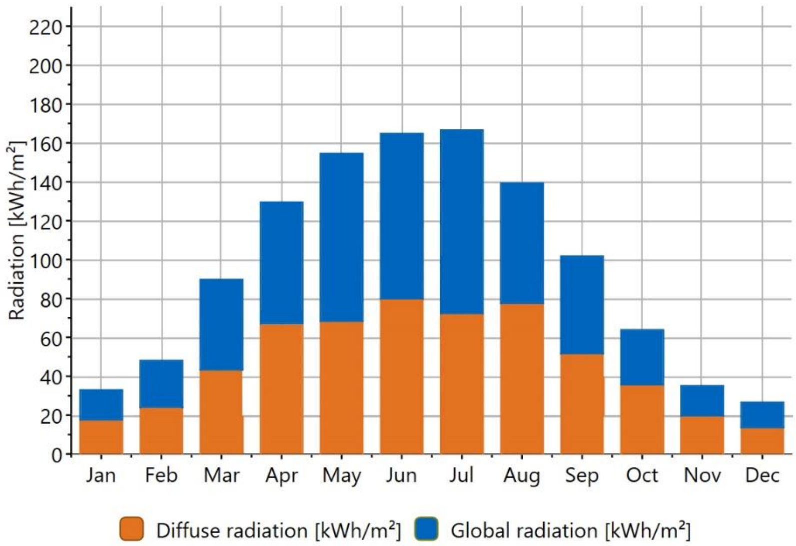


Figure 5.3-5

Radiation chart
Munich, Germany
Source: METEONORM:
www.meteonorm.com

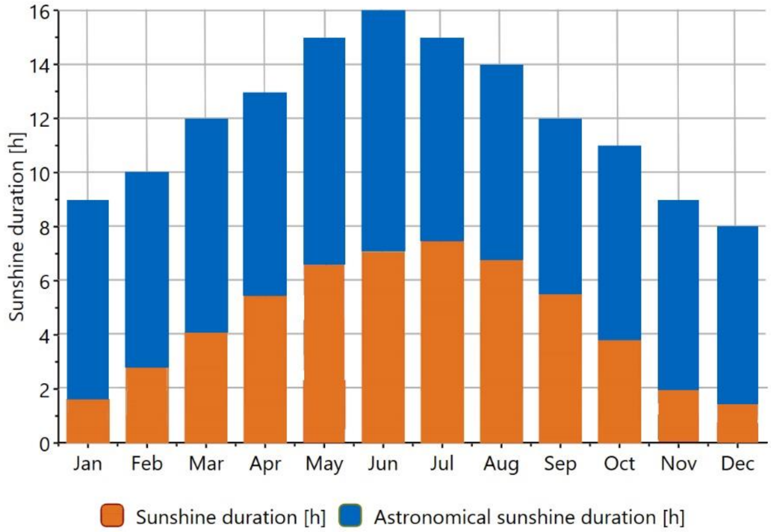


Figure 5.3-6

Monthly average
sunshine duration
Munich, Germany
Source: METEONORM:
www.meteonorm.com

5.3.2 Space description and design approach

A generic office space was chosen for this case study. The office room was assumed to have the dimensions of 4.00m x 6.50m x 3.00m for the width, depth, and height respectively. Five conventional passive strategies were used in this study which are glazing area (WWR), multi-layered glazing system, shadings, daylighting system, and insulation system. The glazing area is divided into upper and lower parts, where the upper part acts as a clearstory window. Both window parts were introduced to the shading devices separately. The choice of the passive systems and its design parameters was based and guided by an extensive literature review of previous studies, which was discussed in Chapter 2.

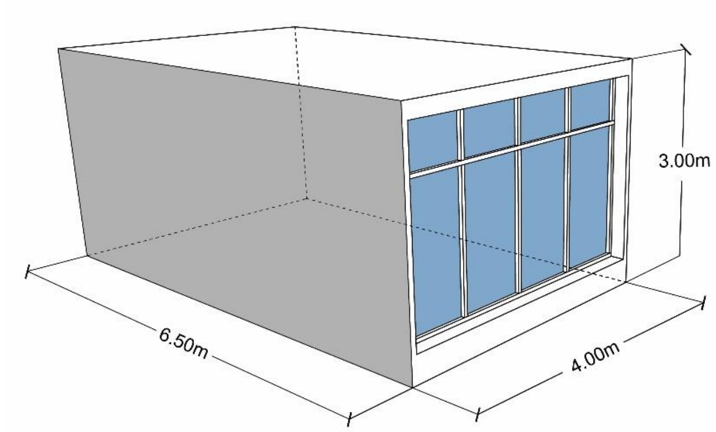


Figure 5.3-7

A perspective view of the studied office room

5.3.3 Methodology

In this case study the IPO framework was used more extensively to optimize the space for three objectives, namely: daylighting, energy, and thermal comfort. A larger pool of options was also explored that has more than 20 thousand distinctive designs.

Parametric Model

A parametric model for the south facing single office space was created using Grasshopper plugin for the Rhino 3D CAD software. Seven Window-to-Wall Ratios were studied together with four glazing systems, four shading systems for each of the windows, and four light-shelf settings. Additionally, the building insulation was increased gradually with 2.5 cm steps until it reaches a total of 25 cm. Overall nearly 20,000 design alternatives could be generated. The details of the parameters are described in the following figure and table (Figure 5.3-8, Table 5.3-1).

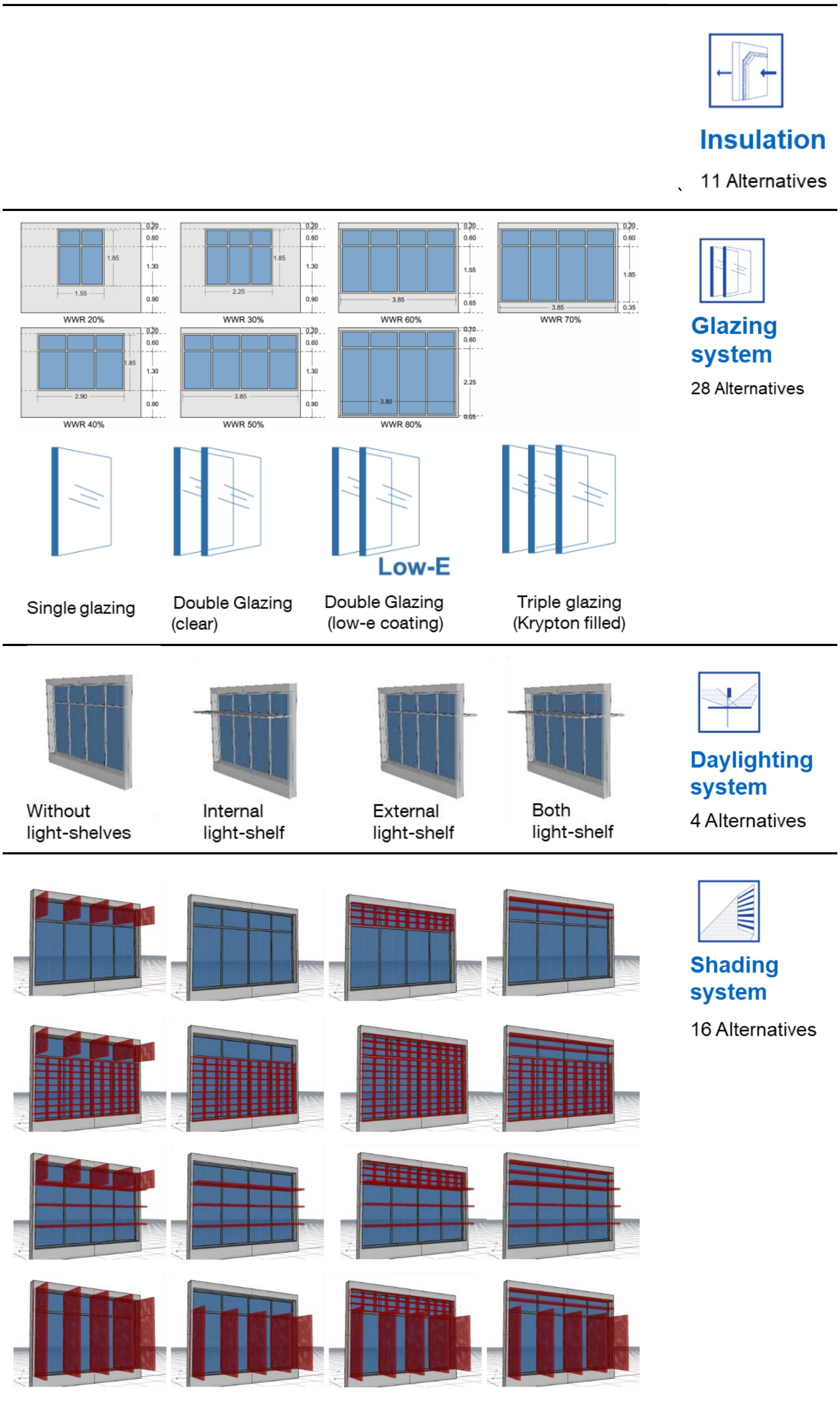


Figure 5.3-8
Categories and visualization of the design variables

Table 5.3-1

Design variables of the case study and their corresponding ranges and values

Design Variable	Type	Possible Values	No. of options
WWR	Continuous	From 10% to 80% (10% step)	7
Insulation Thickness	Continuous	From 0.0 to 25.0 cm (2.5 cm step)	11
Glazing system	Discrete	- Single glazing - Double Glazing - Double Glazing with low-e coating - Triple glazing	4
Shading systems (for each window)	Discrete	- No shading - Horizontal shades - Vertical shades - Solar screen	16 (4x4)
Daylight systems (light-shelves)	Discrete	- No light-shelf - External - Internal - External and internal	4
Total number of design alternatives			19,712

Base case

A base case was defined to make it easier to evaluate and compare the different design alternatives. It was assumed to have an uninsulated external wall, a WWR of 20%, with double glazing, and without any shadings or light-shelves.

Daylighting Simulation Methodology

Daylight performance was evaluated using the IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) criteria. Occupancy hours were assumed to be daily from 8 AM to 6 PM with daylight-saving time. The calculations were made for a reference plane of 60 measuring points in a grid of 0.6m* 0.6m, at a working-plane of 0.85 m height. Simulation parameters are shown in table (5.3-2), and the optical properties of the materials used are presented in table (5.3-3). Solutions that achieve sDA ≥ 50% were considered acceptable, while design alternatives with sDA≥75% were preferred.

Table 5.3-2

Radiance simulation parameters

Ambient bounces	Ambient divisions	Ambient sampling	Ambient accuracy	Ambient resolution
6 / 0 (sDA /ASE)	1000	20	0.1	300

Energy Simulation Methodology

Energy simulations were conducted using EnergyPlus through the Ladybug+Honeybee plugin. The energy use for each design alternative was calculated hourly for the entire year for cooling, heating, lighting and equipment loads. The end use energy per floor area unit (EUI) was used to compare the efficiency of each design. All surfaces of the tested office space were assumed adiabatic, except the external wall with the glazing. The detailed thermal properties are described in table (5.3-2). Equipment loads were assumed to be 8 W/m^2 and the lighting power density 11.8 W/m^2. Lighting load schedules were obtained from the daylighting simulation and the occupancy and equipment load schedules were identical to those used in daylighting simulation. During occupied hours it is assumed that 4 people are present. The office space was considered to be fully air-conditioned and the HVAC cooling and heating setpoints were set at 24°C and 20°C respectively.

Table 5.3-3

The optical and thermal properties for the case study building materials

Building element	Properties	
Glazing	Single glazing	τ_{vis}= 0.88; SHGC= 0.82; U-Value= 5.82 W/m^{2}K
	Double Glazing clear	τ_{vis}= 0.80; SHGC= 0.72; U-Value= 2.71 W/m^{2}K
	Double Glazing low-e coating	τ_{vis}= 0.65; SHGC= 0.28; U-Value= 1.63 W/m^{2}K
	Triple glazing Krypton filled	τ_{vis}= 0.47; SHGC= 0.23; U-Value= 0.57 W/m^{2}K
External Wall	Medium colored with 35% reflectance; 20cm Concrete block + 2cm cement plaster each side (U-value = 3.1 W/m^{2}K); Thermal Insulation thickness (0cm to 25cm); Insulated walls U-Values: 0.91 to 0.114 W/m^{2}K	
Internal Walls	Medium colored with 50% reflectance; adiabatic	
Ceiling	White colored with 80% reflectance; adiabatic	
Floor	Carpet floor with 20% reflectance; adiabatic	
External ground	Dark colored with 20% reflectance	
Furniture	Medium colored with 50% reflectance	
Horizontal Shadings	Medium colored with 50% reflectance; vertical shading angle = 45°	
Vertical Shadings	Medium colored with 50% reflectance; horizontal shading angle = 45°	
Solar Screen	Medium colored with 50% reflectance; perforation ratio: 80%; openings proportion: 2:1 (H:V)	
Light-shelf	High-reflective surface with 90% reflectance	

Thermal comfort

Thermal comfort was evaluated using the Predicted Mean Value model (PMV). The PMV comfort calculator from the Ladybug+Honeybee plugin was used to calculate the Percentage of People Dissatisfied (PPD) for each hour. Operative temperature mean radiant temperature and relative humidity were obtained from the energy simulation, while both metabolic rate and clothing level were set to 1 *mat* and 1 *clo* respectively. Percentage of Discomfort Hours (PDH), which is the percentage of hours that had PPD more than 10%, was aimed to be minimized.

Multi-objective optimization workflow

In this case study, as the number of results is significant, a genetic algorithm was used for optimization to limit the number of simulated cases. Multi-objective optimization was performed using the Grasshopper's plug-in Octopus which is based on the evolutionary algorithm SPEA-2 and applies evolutionary principles to provide Pareto-optimal solutions. Annual Sunlight Exposure was used as a Boolean objective, so that only cases that achieved ASE less than 10% were considered in the optimization. Optimization was performed for the previously mentioned variables and three objective functions were used: the sDA, EUI and PDH. For each of the two studied locations, the optimization process continued for 10 generations with a population size of 30. The mutation rate was set as 0.5, mutation probability as 0.1 and crossover as 0.8. The optimization workflow is shown in figure (5.3-9). Results were then exported to Excel and analyzed using the web-based application "Pollination" to create parallel coordinates graphs (Pollination, 2015).

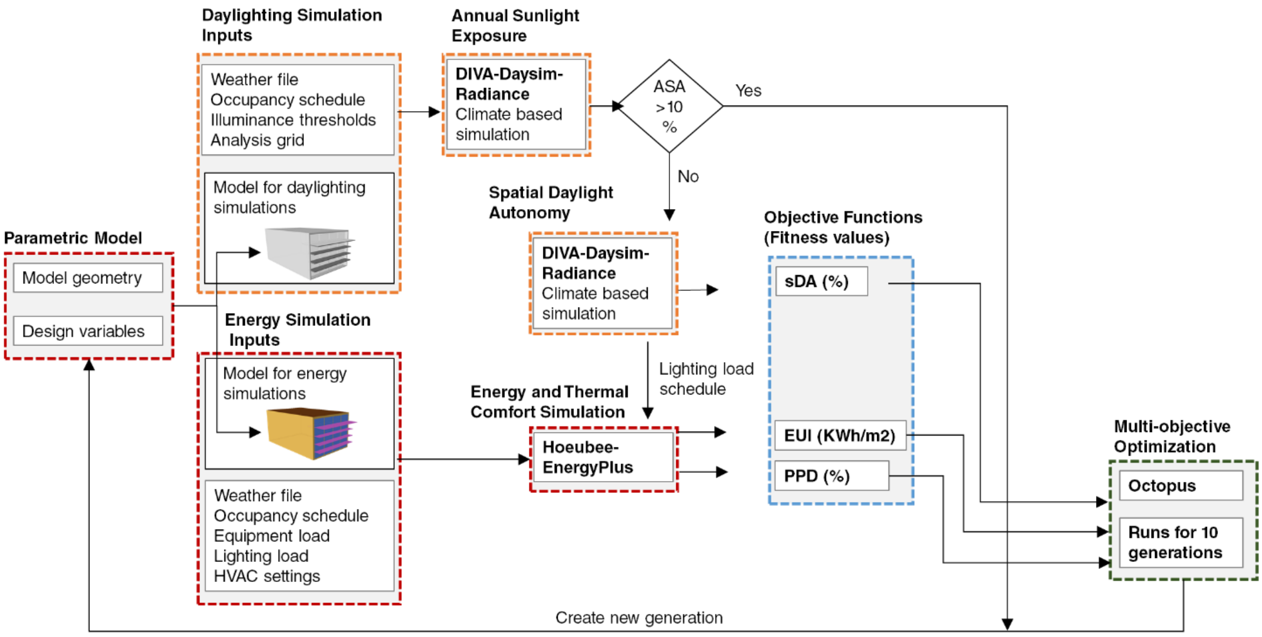


Figure 5.3-9

Optimization process diagram

5.3.4 Results

Simulation and optimization results for Cairo

Base Case

The base case was found to have an acceptable daylight autonomy with sDA= 65%. However, the overall daylighting performance was considered unacceptable due to the high penetration of sunlight (ASE = 28%). It had a high energy use of 193 kWh/m2/year, and a very poor thermal comfort performance (PDH 70%). The main reason behind such poor results was primarily the lack of proper wall insulation and shading.

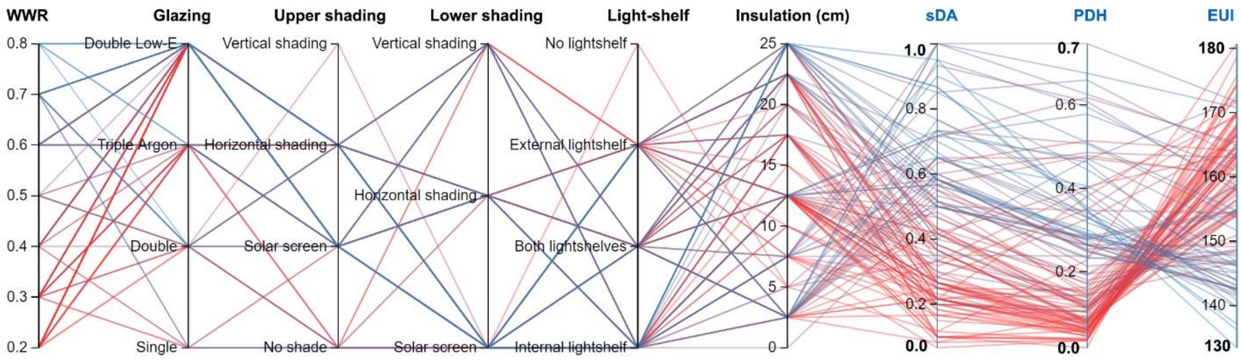
Design space exploration

The optimization process resulted in a wide range of alternatives, 133 of which had ASE<10%. These were the cases which were further studied.

The tabulated data were sorted in Excel, and together with an interactive parallel coordinated graph (Figure 5.3.-10), were used to obtain quick information from the entire data set. The first six vertical axes represent the design variables, while the last three show the range of the design objectives (sDA, PDH and EUI). From the graph it can be noted that the results had a wide range of spatial daylight autonomy percentage that ranged from 7% to 100%. The lowest energy use intensity was 133 kWh/m2/year while thermal comfort ranged between 2% and 75% PDH. Design alternatives and combinations that achieved the highest performance were obtained using the results of the optimization (Pareto optimal solutions) as well as filtering the data for the objectives separately and combined.

Figure 5.3-10

Parallel coordinates diagram for the full spectrum of the optimization results. The range and distribution of the cases for each objective are displayed.



Daylighting

Fifty-four cases achieved the daylighting threshold and nearly quarter of the cases had better performance than the base case. Cases with preferred daylighting performance tended to have a 50% to 80% WWR, with single, double glazing or Low-E coated double glazing. Shadings and light shelves were present in almost every case with few exceptions where it was not needed for the upper window. Three cases achieved the maximum sDA of 100%. This is a considerable enhancement given that these cases also had ASE less than 10% and a slightly higher energy use than the base case.

Figure 5.3-11

Cases with <u>preferred</u> daylighting

Brushes (filters):
sDA ≥ 75%

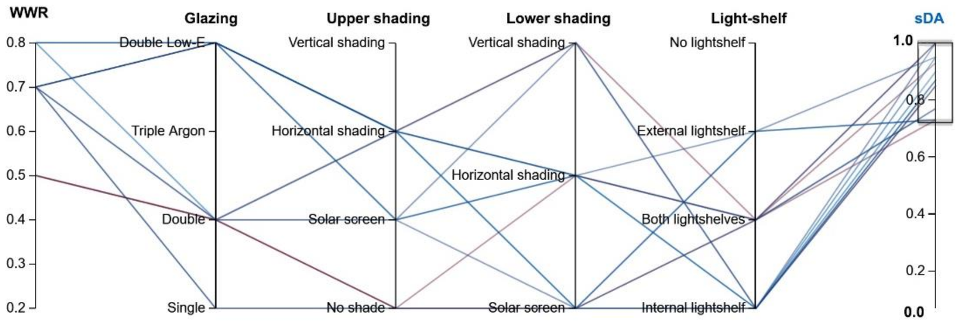
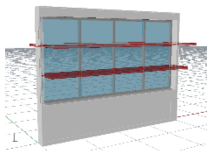
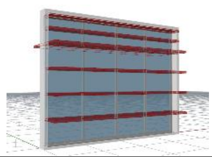


Table 5.3-4

Façade designs, variables and daylighting performances for cases with the highest daylighting performance

Cases with the highest daylighting performance			
Façade Design			
Design Variables			
WWR	0.7	0.50	0.8
Glazing	Single	Double	Double Low-E
Upper-shading	No shade	No shade	Horizontal shadings
Lower-shading	Solar screen	Horizontal-shadings	Horizontal shadings
Light-shelf	Both light-shelves	Both light-shelves	Internal light-shelf
Daylighting Performance	**sDA = 100%**	**sDA = 100%**	**sDA = 95%**

Energy Use

Energy savings reached more than 30%. Thermal insulation was present in all cases with an average of 12.5 cm thickness. It played an important role in reducing the end use energy consumption. Cases with the lowest EUI (133 and 136 kWh/m2/year) had maximum insulation thickness (25 cm). Nevertheless, several cases achieved low EUI with lower insulation thicknesses. The combined effect of high-performance glazing with shading and light shelves facilitated the increase of the WWR without compromising the energy use, and cases with lowest energy use tended to have larger windows (60-80%). That is mainly because shaded glazing with low U-value helped in maintaining the cooling loads at almost a constant level while large glazing area provided significant savings in lighting loads.

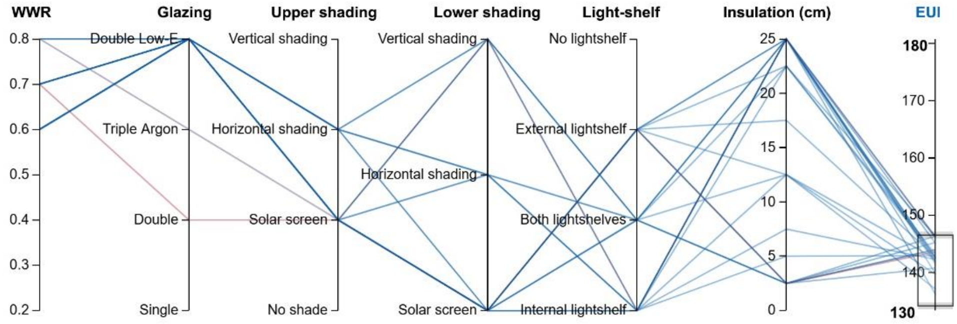


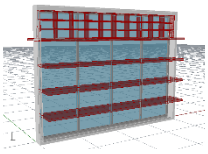
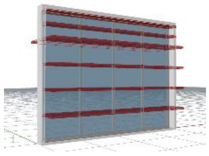
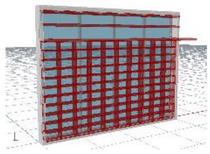
Figure 5.3-12

Case with the <u>lowest</u> Energy Use Intensity (EUI).

Brushes (filters):
EUI<146 kWh/m2/year (25%)

Table 5.3-5

Façade designs, variables and energy savings for cases with the highest energy savings (lowest EUI)

Cases with the highest energy savings			
Façade Design			
Design Variables			
WWR	0.8	0.8	0.8
Glazing	Double Low-E	Double Low-E	Double Low-E
Upper-shading	Solar screen	Horizontal shading	Horizontal shading
Lower-shading	Horizontal shading	Horizontal shading	Solar screen
Light-shelf	Internal light-shelf	Internal light-shelf	External light-shelves
Insulation	25 cm	25 cm	12.5 cm
Energy savings	**31%**	**29%**	**29%**

Thermal Comfort

Thermal comfort was enhanced steadily throughout the optimization where PDH reached a minimum of 2%. However, most of the cases under the 20% benchmark did not achieve sufficient daylighting. The lowest possible PDH with sufficient daylighting performance was found to be 14%, which is still a significant enhancement compared to the base case.

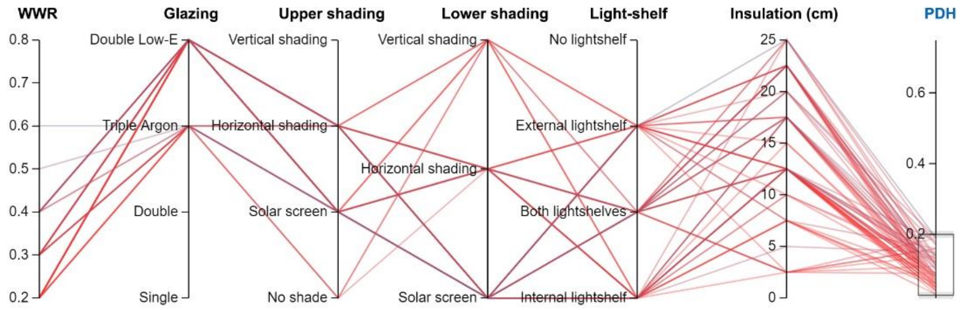


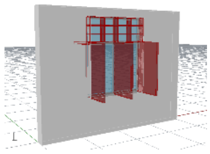
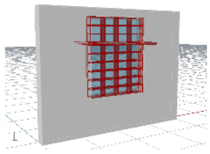
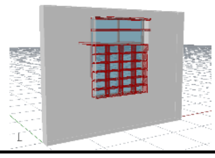
Figure 5.3-13

Cases with the best thermal comfort.

Brushes (filters):
PDH < 20%

Table 5.3-6

Façade designs, variables and thermal comfort performance for cases that achieved best thermal comfort.

	Cases with the best thermal comfort		
Façade Design			
Design Variables			
WWR	0.20	0.20	0.20
Glazing	Triple Argon	Double Low-E	Triple Argon
Upper-shading	Solar screen	Solar screen	Horizontal shading
Lower-shading	Vertical shading	Solar screen	Solar screen
Light-shelf	External light-shelf	Both light-shelves	Internal light-shelf
Insulation	22.5 cm	12.5 cm	7.5 cm
Thermal comfort	**PPD = 14%**	**PPD = 30%**	**PPD = 30%**

Pareto-optimal

Thirty-six Pareto-optimal solutions were found, from which eleven cases achieved a satisfactory sDA of 50% or more. Most of the optimal solutions had WWR between 60-80%, double Low-E glazing, and shadings on the upper and lower parts of the window. Thermal insulation was also present in all optimal cases with a thickness of 12.5 cm or larger. The acceptable optimal solutions are presented in table (5.3-7). Table (5.3-8) shows 3D representations and the trade-off between the three objectives. It also presents a radar-chart comparison between each optimal case and the average performances of all cases. Optimal case performance is represented by the continuous orange-colored lines and the average in blue-dashed lines.

Table 5.3-7

Design variables and objectives values for Pareto-optimal solutions in Cairo.

WWR	Glazing	Upper-Shading	Lower- Shading	Light-shelf	Insulation (cm)	sDA (%)	1-PDH (%)	Energy Savings
0.80	Double Low-E	Horizontal shadings	Horizontal shadings	Internal	25	95%	65%	25%
0.80	Double Low-E	Solar screen	Horizontal shadings	Internal	25	87%	65%	26%
0.80	Double Low-E	Horizontal shadings	Solar screen	External	12.5	73%	67%	24%
0.60	Double Low-E	Horizontal shadings	Vertical shadings	Both	25	67%	74%	21
0.70	Double Low-E	Horizontal shadings	Vertical shadings	Both	22.5	70%	67%	21
0.60	Double Low-E	Horizontal shadings	Solar screen	External	25	60%	73%	22
0.60	Double Low-E	Solar screen	Solar screen	External	22.5	58%	75%	21
0.40	Double Low-E	Solar screen	Vertical shadings	Internal	12.5	57%	79%	18
0.60	Double Low-E	Solar screen	Horizontal shadings	Internal	12.5	65%	67%	21
0.80	Double Low-E	Solar screen	Solar screen	Both	12.5	57%	70%	23
0.70	Single	No shade	Solar screen	Both	2.5	100%	38%	9

Table 5.3-8

Optimal façade designs and their corresponding design variables and performance.

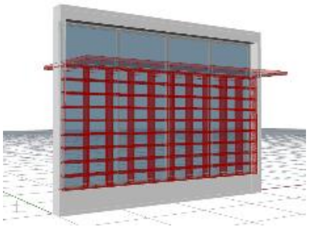
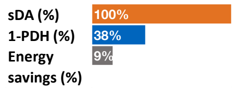
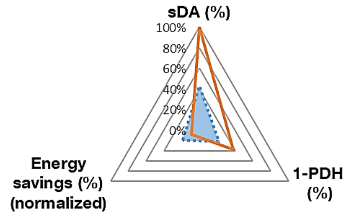
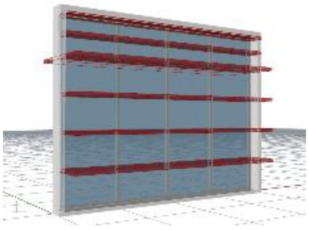
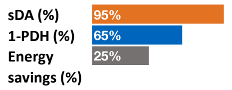
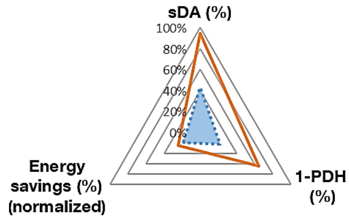
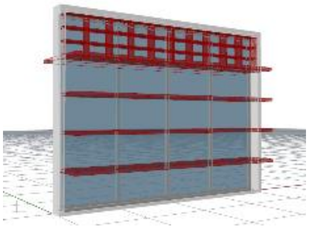
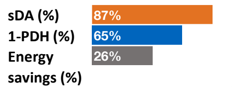
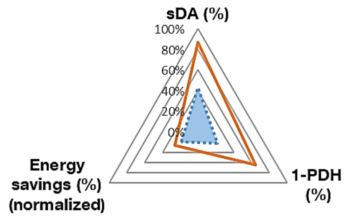
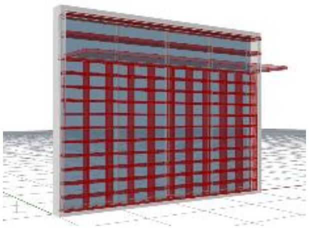
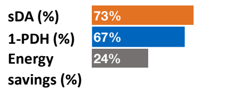
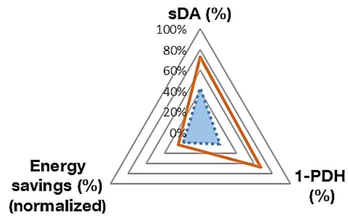
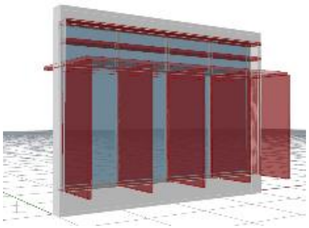
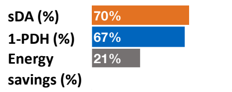
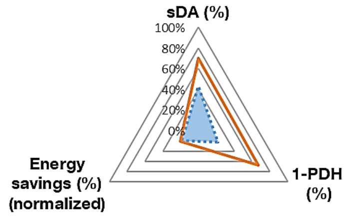
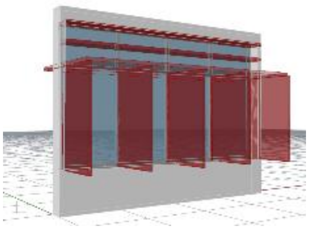
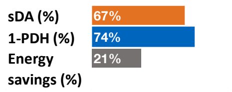
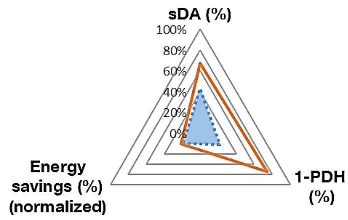
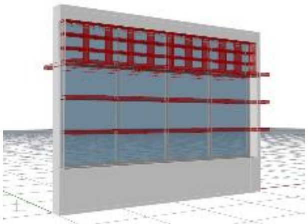
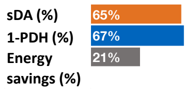
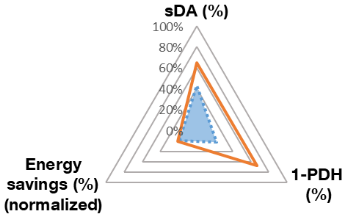
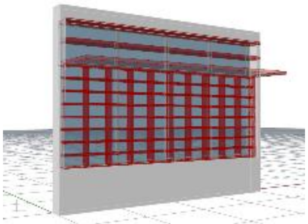
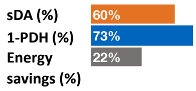
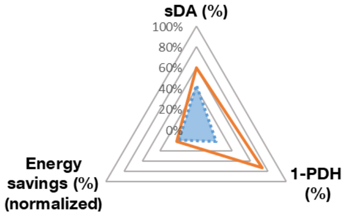
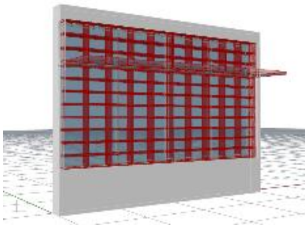
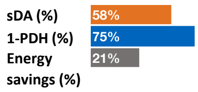
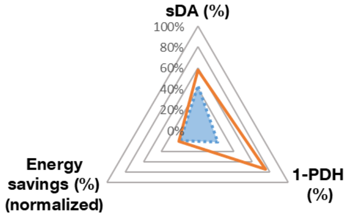
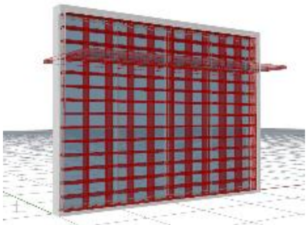
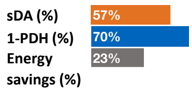
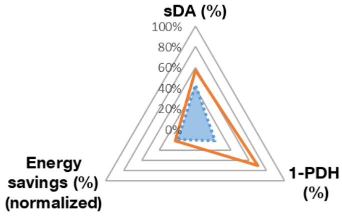
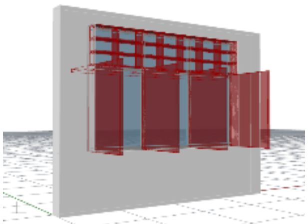
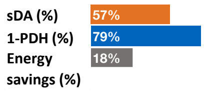
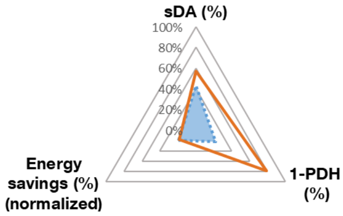
3D Visualization	Design Variables		Objectives performances	Radar-chart (Optimal design compared to average performance)
	WWR: Glazing: Upper-shading: Lower-Shading: Lightshelf: Insulation Thickness:	**0.70** **Single** **No shade** **Solar screen** **Both** **2.5 cm**		
	WWR: Glazing: Upper-shading: Lower-Shading: Lightshelf: Insulation Thickness:	**0.80** **Double Low-E** **Horizontal** **Horizontal** **Internal** **25 cm**		
	WWR: Glazing: Upper-shading: Lower-Shading: Lightshelf: Insulation Thickness:	**0.80** **Double Low-E** **Solar screen** **Horizontal** **Internal** **25 cm**		
	WWR: Glazing: Upper-shading: Lower-Shading: Lightshelf: Insulation Thickness:	**0.80** **Double Low-E** **Horizontal** **Solar screen** **External** **12.5 cm**		
	WWR: Glazing: Upper-shading: Lower-Shading: Lightshelf: Insulation Thickness:	**0.70** **Double Low-E** **Horizontal** **Vertical** **Both** **22.5 cm**		
	WWR: Glazing: Upper-shading: Lower-Shading: Lightshelf: Insulation Thickness:	**0.60** **Double Low-E** **Horizontal** **Vertical** **Both** **25 cm**		

Table 5.3-8 (Continued)

3D Visualization	Design Variables		Objectives performances	Radar-chart (Optimal design compared to average performance)
	WWR: Glazing: Upper-shading: Lower-Shading: Lightshelf: Insulation Thickness:	**0.60** **Double Low-E** **Solar screen** **Horizontal** **Internal** **12.5 cm**		
	WWR: Glazing: Upper-shading: Lower-Shading: Lightshelf: Insulation Thickness:	**0.60** **Double Low-E** **Horizontal** **Solar screen** **External** **25 cm**		
	WWR: Glazing: Upper-shading: Lower-Shading: Lightshelf: Insulation Thickness:	**0.60** **Double Low-E** **Solar screen** **Solar screen** **External** **22.5 cm**		
	WWR: Glazing: Upper-shading: Lower-Shading: Lightshelf: Insulation Thickness:	**0.80** **Double Low-E** **Solar screen** **Solar screen** **Both** **12.5**		
	WWR: Glazing: Upper-shading: Lower-Shading: Lightshelf: Insulation Thickness:	**0.40** **Double Low-E** **Solar screen** **Vertical** **Internal** **12.5**		

Simulation and optimization results for Munich

Base Case

The base case achieved an acceptable daylight autonomy (sDA= 55%), however, the ASE reached 23%. This resulted in an EUI of 133.85 kWh/m2/year and low thermal comfort (PDH= 62%).

Design space exploration

During the optimization process, 145 unique cases with ASE<10% were generated. Daylight autonomy ranged from 7% to 85%. The lowest Energy use intensity was 91 kWh/m2/year. Thermal comfort ranged from 27% to 69%. Thirty-one Pareto-optimal solutions were produced from the optimization. However, only six cases achieved an acceptable sDA. Figure (5.3-14) shows the full range of solutions resulted from the optimization.

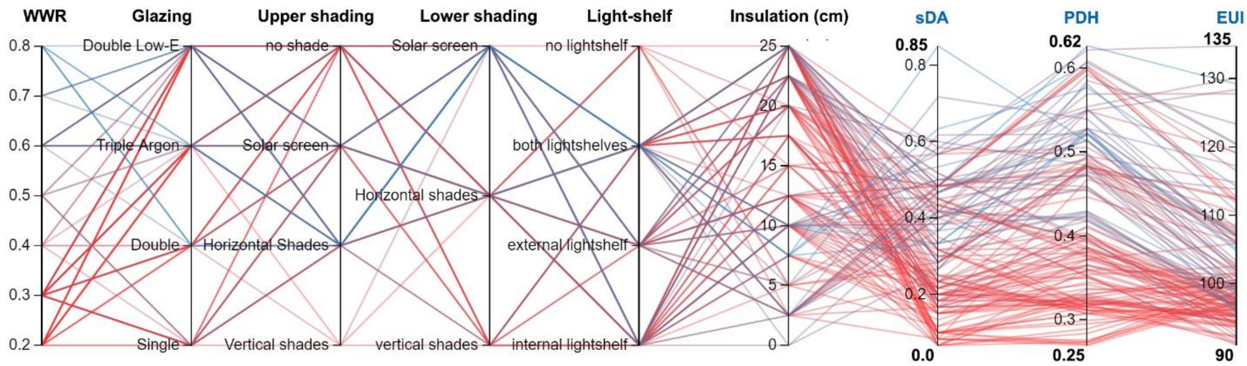


Figure 5.3-14

Parallel coordinates diagram for the full spectrum of the optimization results. The range and distribution of the cases for each objective are displayed.

Daylighting

The maximum achieved sDA was 85%. Several design alternatives with different WWR and glazing types achieved acceptable sDA, except for cases with WWR equal to 20% and 40%. For the upper window, solar screen, horizontal shading, and even unshaded glazing were found to be useful. On the other hand, cases with unshaded lower window, vertical shadings or without light-shelves had a high penetration of direct sunlight that resulted in a high ASE and therefore were excluded during the optimization. Light-shelves, in particular, were found to be effective, as all successful cases had light-shelves.

Figure 5.3-15

Case with the <u>accepted</u> daylighting performance.

Brushes (filters):
sDA ≥ 50%

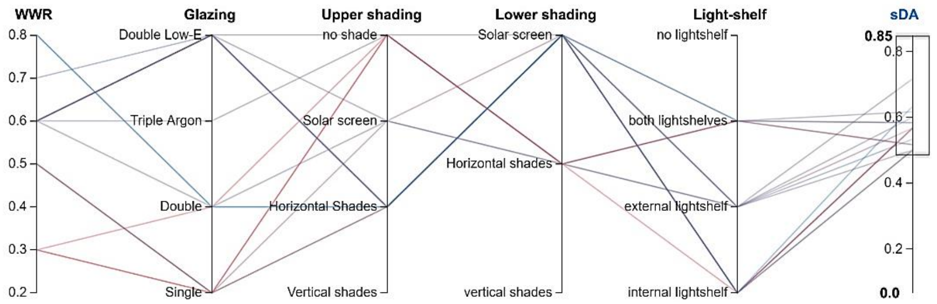
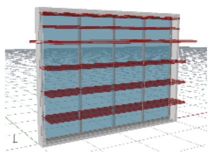
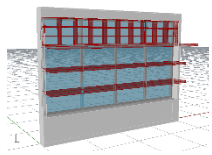
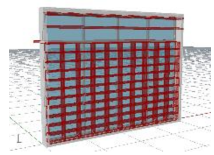


Table 5.3-9

Façade designs, variables and daylighting performances for cases with the highest daylighting performance

Cases with the highest daylighting performance			
Façade Design			
Design Variables			
WWR	0.80	0.60	0.80
Glazing	Double	Double	Double
Upper-shading	Horizontal shades	Solar screen	Horizontal shades
Lower-shading	Horizontal shades	Horizontal shades	Solar screen
Light-shelf	Both light-shelves	External light-shelf	Internal light-shelf
Daylighting Performance	**sDA= 85%**	**sDA= 72%**	**sDA= 63%**

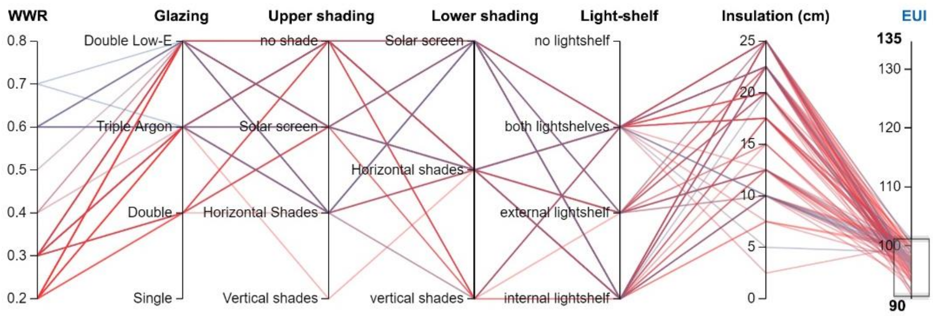
Energy Use

Energy use was reduced drastically throughout the optimization from 133.8 kWh/m2/year to only 91 kWh/m^2/year with also more 30% reduction. The effects of wall insulation and highly efficient glazing are the main reason behind this reduction. It is worth noting that the cases with the least energy use had also much lower WWR, which had a negative effect on the daylighting performance. Nonetheless, one case with 60% WWR achieved sufficient daylighting with only 92.3 kWh/m2/year. Once more horizontal shading and solar screens were found effective.

Figure 5.3-16

Case with the <u>lowest</u> Energy Use Intensity (EUI).

Brushes (filters):
EUI<101 kWh/m2/year (25%)



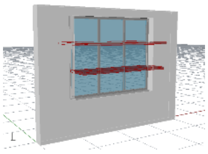
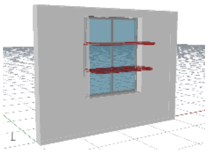
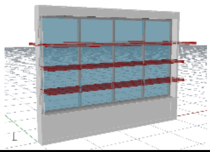
	Cases with the highest energy savings		
Façade Design			
Design Variables			
WWR	0.30	0.20	0.60
Glazing	Double Low-E	Double Low-E	Triple Argon
Upper-shading	No shade	No shade	No shade
Lower-shading	Horizontal shades	Horizontal shades	Horizontal shades
Light-shelf	Both light-shelves	External light-shelf	Both light-shelves
Insulation	25 cm	20 cm	22.5 cm
Energy Savings	32%	32%	31%

Table 5.3-10

Façade designs, variables and energy savings for cases with the highest energy savings (lowest EUI).

Thermal comfort

Thermal comfort was enhanced gradually, yet enhancements were mainly connected to the reduction in the WWR. That resulted in an inverse proportional relation between daylighting and thermal comfort. As a result, despite the PDH reached a minimum of 27%, cases that achieved acceptable daylighting had a minimum of 40% PDH. Further enhancements to the HVAC system might be needed in this case.

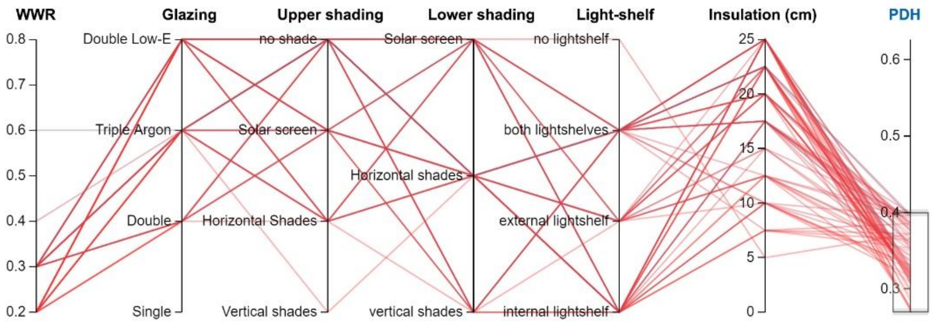


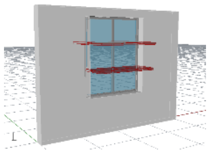
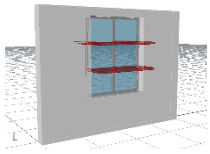
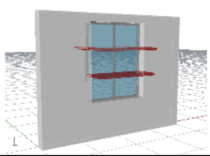
Figure 5.3-17

Cases with the best thermal comfort.

Brushes (filters):
PDH < 40%

Table 5.3-11

Façade designs, variables and thermal comfort performance for cases that achieved best thermal comfort.

	Cases with the best thermal comfort		
Façade Design			
Design Variables			
WWR	0.20	0.20	0.20
Glazing	Triple Argon	Triple Argon	Triple Argon
Upper-shading	No shade	No shade	No shade
Lower-shading	Horizontal shades	Horizontal shades	Horizontal shades
Light-shelf	Both light-shelves	Internal light-shelf	Both light-shelves
Insulation	25 cm	25 cm	22.5 cm
Thermal comfort	**PPD = 27%**	**PPD = 27%**	**PPD = 27%**

Pareto-optimal

Thirty-one Pareto-optimal solutions were produced from the optimization. However, only six cases achieved an acceptable daylighting performance. While several cases achieved acceptable daylighting and energy savings at the same time, thermal comfort was found to have low performance in almost all cases. Hence, a different approach or additional design strategies might be necessary.

Table 5.3-12
Design variables and objectives values for Pareto-optimal solutions in Munich.

WWR	Glazing	Upper-shading	Lower-shading	Light-shelf	Insulation (cm)	sDA (%)	PDH (%)	EUI (kWh/m2/yr)
0.80	Double	Horizontal	Horizontal	Both	7.5	85%	51%	20
0.60	Double Low-E	No shade	Solar screen	Both	2.5	62%	52%	23%
0.60	Double Low-E	Solar screen	Horizontal	External	20	60%	48%	28%
0.30	Single	No shade	Horizontal	Internal	15	57%	51%	20
0.60	Triple Argon	No shade	Horizontal	Both	22.5	52%	40%	31%
0.30	Double	No shade	Horizontal	Both	22.5	52%	39%	29%

5.3.5 Discussion and conclusion

In this case study, the use of the Integrative Performance Optimization (IPO) framework to arrive at high-performance façade designs from a large pool of design options was evaluated. A parametrically modeled office facade was optimized for the climate conditions of Cairo and Munich. The objectives of the optimization were enhancing the daylighting performance, energy use and thermal comfort and several passive strategies were used as the optimization variables.

The results showed the capability of the process to provide several design alternatives with enhanced performance in both case studies. Reduction in energy use reached more than 30% in both cases, while the daylighting performance reached adequate levels with a maximum sDA of 100% and 85% in Cairo and Munich respectively. Thermal comfort had also improved considerably compared to the base case but remained within an unsatisfying level in most cases. Since the cases were assumed to be fully air-conditioned, the HVAC system might also need to be optimized for further enhancement in thermal comfort.

General trends were found to emerge from the results which also coincide with previous research. The effect of wall insulation was obvious in both cases and played an essential role in reducing the energy use. Similarly, High-performance glazing and especially the double glazing with Low-E coating was present in most of the successful cases. The use of shading devices was more effective in the case of Cairo and facilitated the use of larger windows. This can be explained in the light of the excessive presence of sunlight in Cairo where the shading devices and high glazing succeeded in blocking the direct sunlight and reducing solar gain and therefore keeping the cooling loads at almost a constant level. Concurrently, the large glazing area benefited from the available diffused lighting in reducing the lighting load and hence the overall energy consumption. On the other hand, in the case of Munich, lower window-to-wall ratios had better performance, as savings from the use of shadings and high-performance glazing could not match the increase in heating load due to the high window-to-wall ratios. Light-shelves were found to be always useful and were hardly absent in all successful solutions in both cases.

In conclusion, it became apparent that the use of multi-objective optimization for complicated design problems can aid in reaching performative solutions and clarify the relation between the design variables and objectives. The main downside of the optimization process lies in the duration of computation time. The optimization process for each of the two case studies consumed nearly 48 hours on a desktop computer with 1.6 GHz i7 with 6 GB of RAM. This could be a serious obstacle, especially when considering more complex design problems and much larger number of design solutions. Nevertheless, with the continuous improvements in both optimization and simulation tools, a potential for further research is apparent in the diversity of design problems that could be defined and the endless number of variables and objectives that could be investigated.

5.4 Conclusion

The aim of this chapter and the case studies was to assess the usability and efficiency of the developed IPO framework in different design cases. The framework was found useful in arriving at high-performance designs. However, some limitation and areas of enhancements were noticed. The performance and limitations in the areas of modeling, simulation, optimization, and data and results analysis are discussed in the following sections.

5.4.1 Parametric modeling

The use of parametric modeling proved efficient as it provided more flexibility in the designs and the possibility of using hypothetical and real-life design cases. Especially in the first case study, where the performance assessment is for a predesigned case with specific constraints.

5.4.2 Integrative simulation

Connecting the parametric model to several simulation engines required extra steps of model preparations according to the requirements of each simulation software. Nevertheless, once the models are adjusted, changes to the main geometric model are transferred seamlessly to the simulation models. This made it easier and less time consuming to make changes as well as ensuring the exact same inputs to the different simulation engines. The interoperability between the different engines was also considered in the case studies, such as using the output from daylighting assessment for energy simulation. This ensured consistency of the results. The availability of many third-party plugins for the Grasshopper/Rhino ecosystem made it easier to perform diverse simulations without the need to change the software interface. Still, an experienced user with the grasshopper software interface is essential to deal with the framework. To overcome that, a simpler interface could be considered which will be discussed in the next chapter.

5.4.3 Multi-objective optimization

In the second case study, a multi-objective optimization was applied using the plugin Octopus which relies on the genetic algorithm (SPEA 2). The optimizer was found useful in discovering large design spaces with numerous design options and solutions. Several performative designs were achieved, and enhancements could be seen during the optimization process as the optimization tool allowed for continues improvement in the overall performance, which highlights the significance of using optimization tools.

5.4.4 Data and results analysis and visualization

The main drawback of the framework at its current design is in the absence of a user-friendly Graphical User Interface (GUI). Even more than just using a simple interface for entering design inputs, getting useful information directly from the interface to guide the design decision is of significant importance. In both case studies, an excess amount of data from simulation software were manually turned into useful charts that can provide valuable information using other software such as Excel and Design Explorer. In most cases, this process was challenging and time-consuming. A data visualization integrated with the framework can be useful in providing information and real design-decision support without the need for extra work or other software packages. This limitation will be discussed in the next chapter.

Chapter 6: Design Decision Support Tool and Visualization Dashboard

6.1 Introduction

As discussed in the previous chapter, analyzing the results of multi-objective optimization and building performance simulation proves to be a very challenging process that requires navigating between different software and tools. There is a clear demand in design decision support tools that combine methods for big data analysis and provide detailed information for each design and parameter. Having a single platform that provides methods for visualizing and analyzing a large amount of data, clarifies the relationship between objectives and variables, and has the ability to compare and analyze the preferred designs thoroughly, which can facilitate the process of design decision making. In this chapter, previous attempts to develop data visualization tools for both integrated building simulation and optimization outputs were analyzed. Guidelines for an effective visualization system are discussed, and a visualization tool prototype, that can be effective in decision making and in analyzing the of results for multi-objective optimizations, is presented.

6.2 Previous attempts for visualizing building simulation and optimization results[1]

Building Performance Simulation (BPS) is an important tool to support the move towards more energy efficient buildings and is becoming an integral part of the current design decision-making process (Dan Hobbs et al. 2003; Mourshed et al. 2003; Aksamija and Mallasi 2010). BPS software and tools are being rapidly shifted to be more user-friendly and accurate. Despite the

[1] Part of this thesis section was published in Gadelhak, M., Lang, W., & Petzold, F. (2017). A Visualization Dashboard and Decision Support Tool for Building Integrated Performance Optimization. In A. Fioravanti, S. Cursi, S. Elahmar, S. Gargaro, G. Loffreda, G. Novembri, & A. Trento (Eds.), *ShoCK! - Sharing Computational Knowledge! - Proceedings of the 35th eCAADe Conference, 20-22 September 2017* (Vol. 1, pp. 719–728). Sapienza University of Rome, Rome, Italy.

high demand for more user-friendly interfaces, visualization and analysis tools for simulation results are not usually given the deserved attention.

Decision-making and data visualization tools have a significant impact on the final design product. In a recent survey, nearly 25% of participants (architects and engineers) identified graphical representation as their top priority for the user interface of BPS software (Attia et al. 2009). However, another survey showed that most users were not satisfied with the Graphical User Interface (GUI) provided by commercially available tools as 75% of the users pointed out the lack of a graphic interface for post-processing of the BPS optimization results (Attia et al. 2013). Therefore, most of the surveyed users had to depend on their own post-processing skills or self-developed tools to graphically represent the simulation output and to analyze the data.

The scarcity of efficient data analysis and insufficient quality of visualization tools is even more evident in the case of an integrated (holistic) assessment or a multi-objective optimization. In an integrated design assessment, it can be necessary to have a dashboard giving an overview of all the relevant performance aspects and summarizing the performance of the building while simultaneously providing detailed information where needed. On the other hand, analyzing a large number of simulation outputs, such as results from a multi-objective optimization, requires more advanced tools to examine the complete set of data and to find relations between different objectives and variables. While there were some trials to develop data visualization and result-analysis tools for both integrated performance simulation and multi-objective optimization, there is no single visualization tool that combines methods for big data analysis and design decision support through detailed information for each of the relevant aspects. As a result, analyzing the multi-objective optimization results becomes a very difficult process and requires navigating between different software tools and platforms.

6.2.1 Integrated performance dashboards

The importance of integrating graphical representations of diverse performance analysis in a single dashboard was highlighted by many researchers. One of the first examples was developed within the scope of the Daylight-Europe project (DLE), where a multi-parameter dashboard to compare reference and as-built cases "Integrated Performance View (IPV)" was presented (Hensen et al. 1996). This dashboard proved useful in comparing the overall performance of design cases, as it integrated different charts and graphs for heating load, energy consumption, visual comfort, thermal comfort and glare index. The IPV tool was further developed to provide more flexibility and customization as well as several enhancements for better communication with users (Prazeres and Clarke 2005). Struck et al. (2012) built upon this concept with a special focus on human cognition and more innovative graphs, such as temporal maps and motion charts. Other research works and commercial software also offer an integrated performance dashboard. However, most of these tools lack the ability to deal with a large amount of data, and thus cannot be efficiently used to analyze the results of multi-objective optimizations. Other research works on the visualization of building simulation results were considered with single aspect of building performance such as climate data analysis and presentation (Liedl 2016; Winn 2014); energy use (O'Donnell et al. 2013; Ritter et al. 2014); or life-cycle analysis (Kovacic et al. 2016).

6.2.2 Analysis of optimization results

Several research works investigated the analysis of building performance optimization results. Brownlee and Wright (2012) sought to analyze the relationship between design objectives and variables, using a simple ranking order and correlation coefficient. Although it is not conventional to use correlation factors for multivariant problems as it may lead to decisive results, it rendered useful to use a combination of scatter plots and spreadsheets to graphically present the optimization results. Scatter plots, accompanied by parallel coordinates graphs and graphical representations of the design alternatives, were also used by Chaszar et al. (2016). Such graphs provided a useful feedback, but it was noted that adding more interactive capabilities could further enhance the workflow. To help designers better to understand the optimization results, Wortmann (2016) presented a novel method to represent the results graphically. His method, called Performance Map, helps in identifying the optimization problem, relating parameters and performance, examining promising designs, and guiding automated design exploration. Thornton Tomasetti (2017) developed a free online tool (Design Explorer) which also helps in investigating the results of multi-objective optimization. The tool, which was used in the second case study in the previous chapter, provides parallel coordinates graphs with interactivity and filtering options as well as the possibility to combine it with graphical representations and scatterplot diagrams. The tool was found useful, however it still falling short when it comes to analyses of the details of each performance aspect. Other effective methods were also addressed in other engineering disciplines (Pryke et al. 2007; Witowski et al. 2009). Nevertheless, while these methods can simplify analyzing a large number of cases, it does not provide detailed information on each performance aspect. For instance, using scatter plots and parallel coordinates graphs can aid in finding an optimal design for daylighting performance, but it does not show how the daylight is distributed within the space, or at which hours artificial lighting is needed. Such detailed information and context are necessary for the decision-making process. The ability to examine and compare several aspects at the same time is equally important.

6.2.3 Interactivity and visualization techniques

Interactivity plays a major role in the visualization tools. Yi et al. (2007) presented seven interactive techniques that can be effectively applied to the case of building performance optimization. The first four techniques, Select, Explore, Reconfigure and Encode, can help the user to explore the complete set of data by switching between different graphical representations of data and marking preferred designs. The other three techniques Abstract/Elaborate, Filter, and Connect, can be used to provide detailed information for selected cases. Adding two other techniques, such as Compare (for directly comparing selected cases) and Advice (as a tool for guiding further enhancements) allows for quick, yet thorough, comparison between preferred cases, and supports informed decision-making. These two additional techniques were also suggested by Haeb et al. (2014), who highlighted the importance of spatial context and visual feedback as an essential component in the field of building performance simulation.

6.3 Visualization dashboard: guidelines

Building on the reviewed literature, the following guidelines, and requirements for a new tool for visualizing the results of integrated building performance optimizations were defined. The suggested visualization tool can provide better ways to investigate the building optimization results by offering three levels of data analysis:

6.3.1 Design space overview and exploration

At the first level, the full set of simulation results should be explored. Multi-dimensional graphs, such as parallel coordinates and scatter plots are useful in this case. Switching between plot types, filtering the results and selecting favorite cases help in clarifying basic relations between the objectives and variables, in addition to highlighting optimal and preferred designs.

6.3.2 Sensitivity analysis and parameter relations

On the second level, the direct relation between any two variables or objectives can be investigated. The use of sensitivity analysis and 2D charts indicates the variables that drive the optimization process, the expected enhancement in each objective, and the relative importance of the design variables.

6.3.3 Detailed results and comparison between favorite designs

At the final level, an integrated dashboard is presented with detailed performance data, which provides all the needed information about each selected design. To ensure an informed decision-making process, the visualization tool should offer the ability to compare the detailed performance and contextual reference (images and 3D model of the cases) of favorite cases.

Figure (6.3-1) shows a preliminary conceptual sketch for the anticipated visualization tool.

6.4 Visualization dashboard: prototype

As a proof of concept, a preliminary prototype was developed according to the above-mentioned guidelines. The prototype was built using the Visual Language Programming tool Grasshopper and HumanUI, a plugin for Grasshopper that enables the creation of graphical user interfaces. Additional customized Grasshopper user objects and code functions were written to overcome limitations in the HumanUI Plugin. Figure (6.4-1) shows the main tool screen. The visualization tool consists of the following panels: Context and design parameters panel; Explore panel; Variable-objective relation panel; Compare panel; and the Integrated dashboard.

6.4.1 Context and design parameters panel

The left panel shows the names of the selected design alternatives as well as a zoom-able and rotational 3D visualization and the corresponding design parameters. The user can change the design parameters to change the selected design alternative according to specific design parameter without the need of any experience with 3D or parametric modeling. (Figure 6.4-1-A).

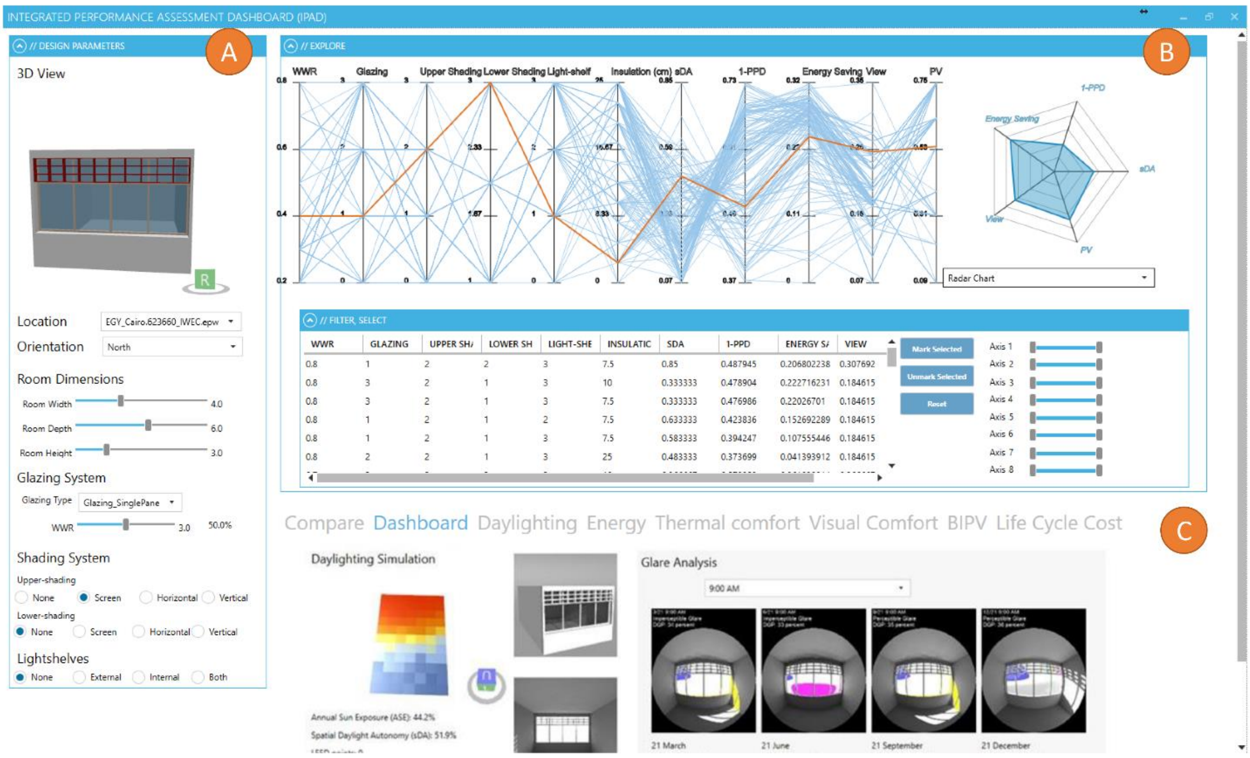


Figure 6.4-1

A screenshot of the visualization tool. A- Context and design parameters panel, B- Explorer panel, and C-Integrated dashboard

6.4.2 Explore panel

Alternatively, the user might choose to select the design from the Explore section. The explore section contains a parallel coordinates chart that shows the design variables and results of the complete design set with the selected design highlighted. It also contains a radar or bar chart for showing the performance of the selected design as well as a data table. The parallel coordinates chart offers an interactive tool by which the results could be filtered for a specific range of values for any and each of the variables and objectives. Additionally, the results in the data table could be sorted for any of the variables and objectives. A radar chart for the objective results is also shown for the selected design alternative. It is also possible to mark cases which will be compared later to each other (Figure 6.4-1-B). In order to create this panel, several customized components were created in grasshopper and Python to create the graphs.

6.4.3 Variable-objective relations panel

In this panel, the user can choose variable(s) and objective(s) to see the direct relation between each other, which is rendered in the shape of a 2D scatterplot chart in case of a single variable and single objective, or as a matrix of scatterplots in case of several variables and objectives. This panel opens in a separate window and depends on the Mandrill plugin for the scatterplot matrix charts. For instance, the scatter plot between the energy savings and glazing and insulation for case study two in the previous chapter shows how triple and double Low-E glazing have a higher potential for energy savings compare to single and conventional double glazing. For the insulation, it could be noted that the potential for energy savings increase with the increase of the insulation thickness. It is important to note, however, that due to the multivariant and multi-objective optimization general and direct correlation should not be deduced from the chart. (Figure 6.4-2).

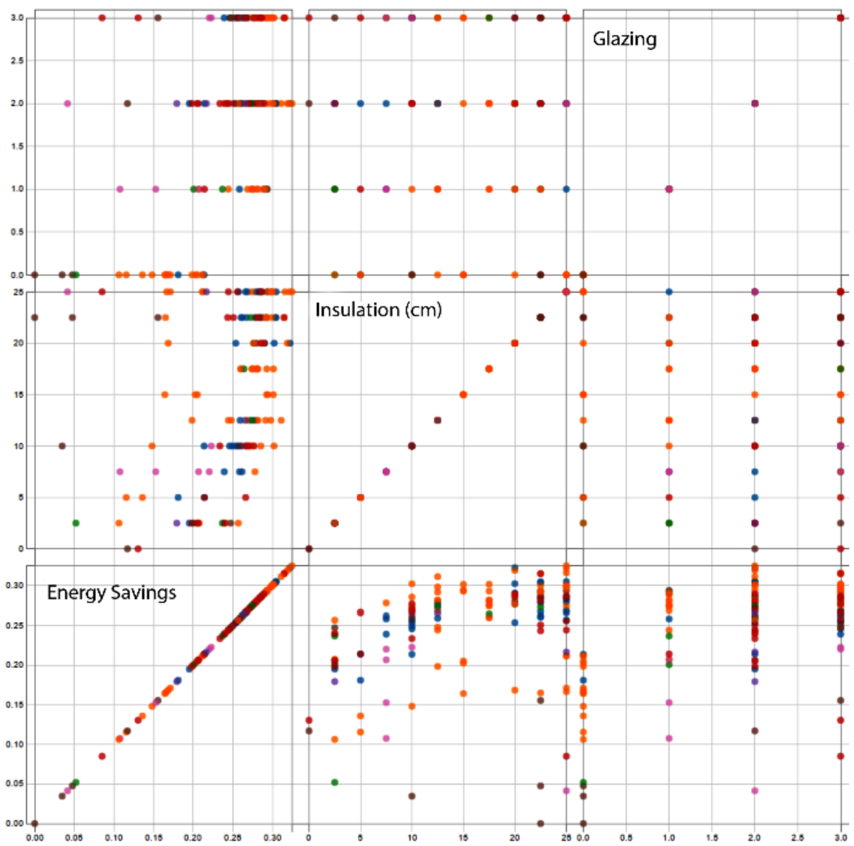


Figure 6.4-2

Scatterplot matrix chart showing the relation between energy savings, insulation and glazing type.

6.4.4 Compare panel

To compare the performance of the preferred designs, marked cases are automatically added to the compare panel, where a simple bar or radar chart comparison is created as well as a 3D representation to each design alternative (Figure 6.4-3). All the cases are also ordered using a stacked bar chart (Figure 6.4-4). That overall performance can be ordered by sorting the total sum of the normalized result of each aspect, similar to the method used in (Gratzl et al. 2013). The ranking equation is as follows:

Equation 6.4-1

Summation of the normalized values of the performance aspects results (The ranking equation).

$$\sum_{i=0}^{n} X_i$$

Where:

Equation 6.4-2

Normalization equation for each performance aspect result.

X_i is the normalized value each aspect result and is defined by the equation:

$$X_i = \frac{x_i - x_{min}}{x_{max} - x_{min}}$$

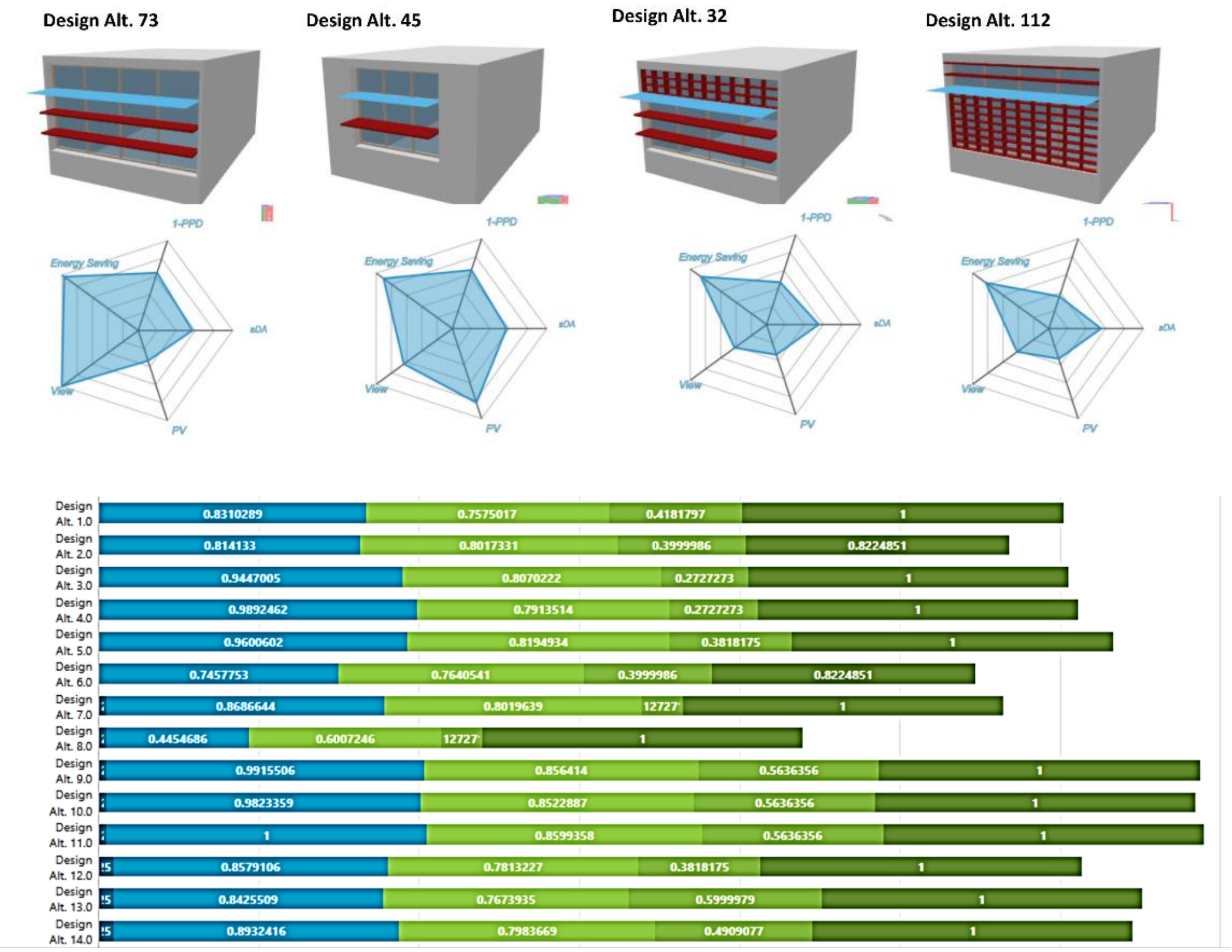


Figure 6.4-3

A comparison between different design alternative with similar energy savings. Stacked bar comparison is also used for comparing the overall performance of the design alternatives

6.4.5 Integrated dashboard and performance objectives tabs.

Similar to the IPV tool discussed earlier in section (6.2) of this chapter, the integrated dashboard displays a collection of charts to provide a holistic overview of the performance of the selected design alternatives. For each performance objective, a separate section (tab) that includes alternative ways of result visualizations and an even higher detail of result analysis is provided. simulation outputs can also be investigated such as lighting and occupancy schedules; heating, cooling and equipment's load; alternative daylighting performance metrics like the daylight autonomy, daylight availability, ... etc.; and glare analysis for various times and dates to name a few.

Daylighting

In the daylighting tab the results of daylighting simulation are provided as numerical data (percentage of space with adequate daylighting) as well as 2D and 3D visualizations of the spatial distribution of daylight in the space. The user can switch between different dynamic annual metrics as well as illuminance values at specific time. Both visualizations can be zoomed and rotated to make it easier for the user to investigate. Daylighting simulation settings and inputs can also be controlled from a pop-up window from this panel.

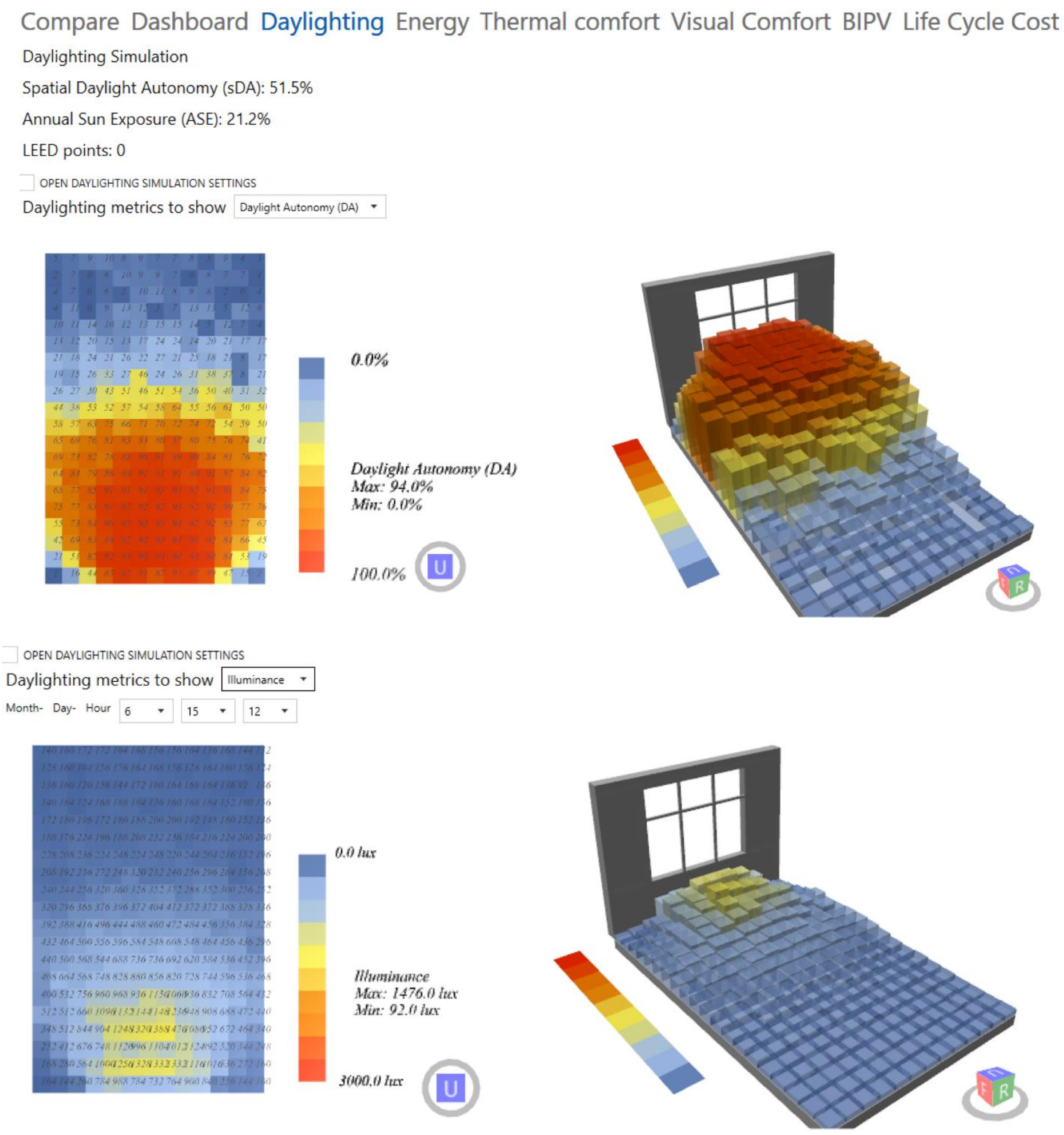


Figure 6.4-4

Screenshot of the daylighting tab from the integrated dashboard showing a representation for both an annual daylight metric as well as illumination on a specific date and time.

Energy

The energy tab provides information on the annual energy consumption of the selected design. That includes the total annual energy use, and the use per square meter as well as monthly load consumption for each of the four main loads, cooling, heating, lightning and equipment load. It also shows the percentage of consumption per category. Similar to the daylighting tab, the simulation settings and inputs can also be controlled from this tab.

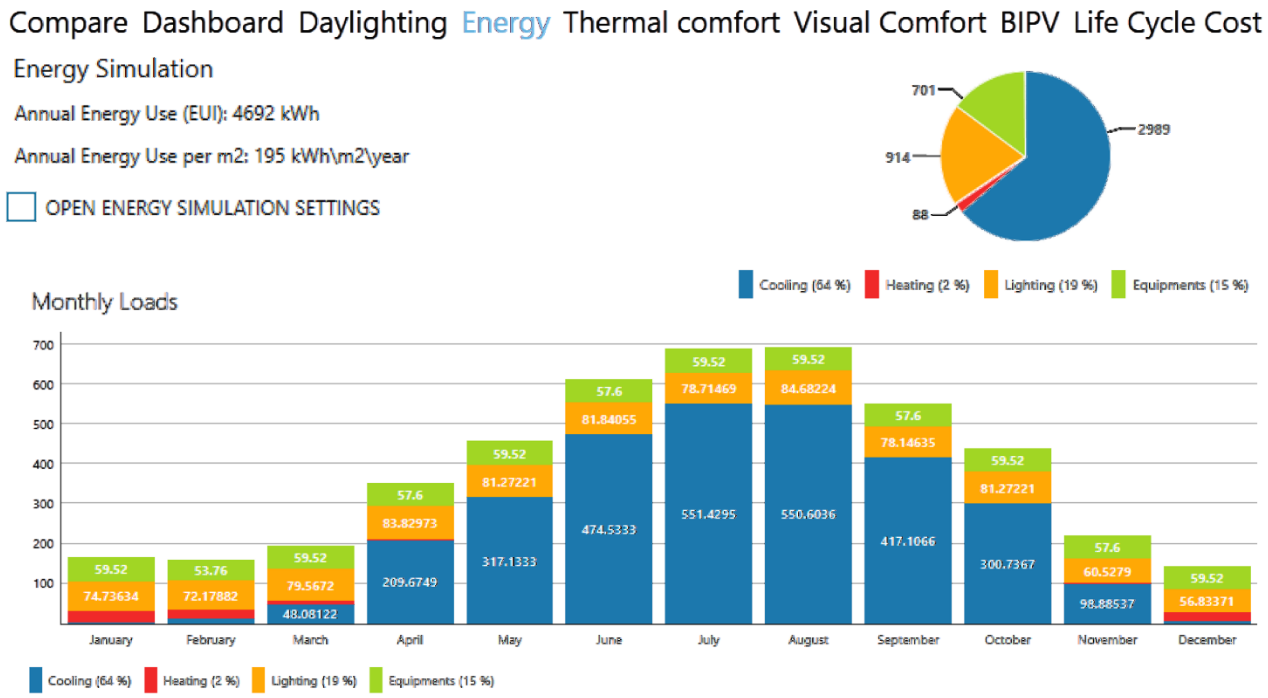


Figure 6.4-5

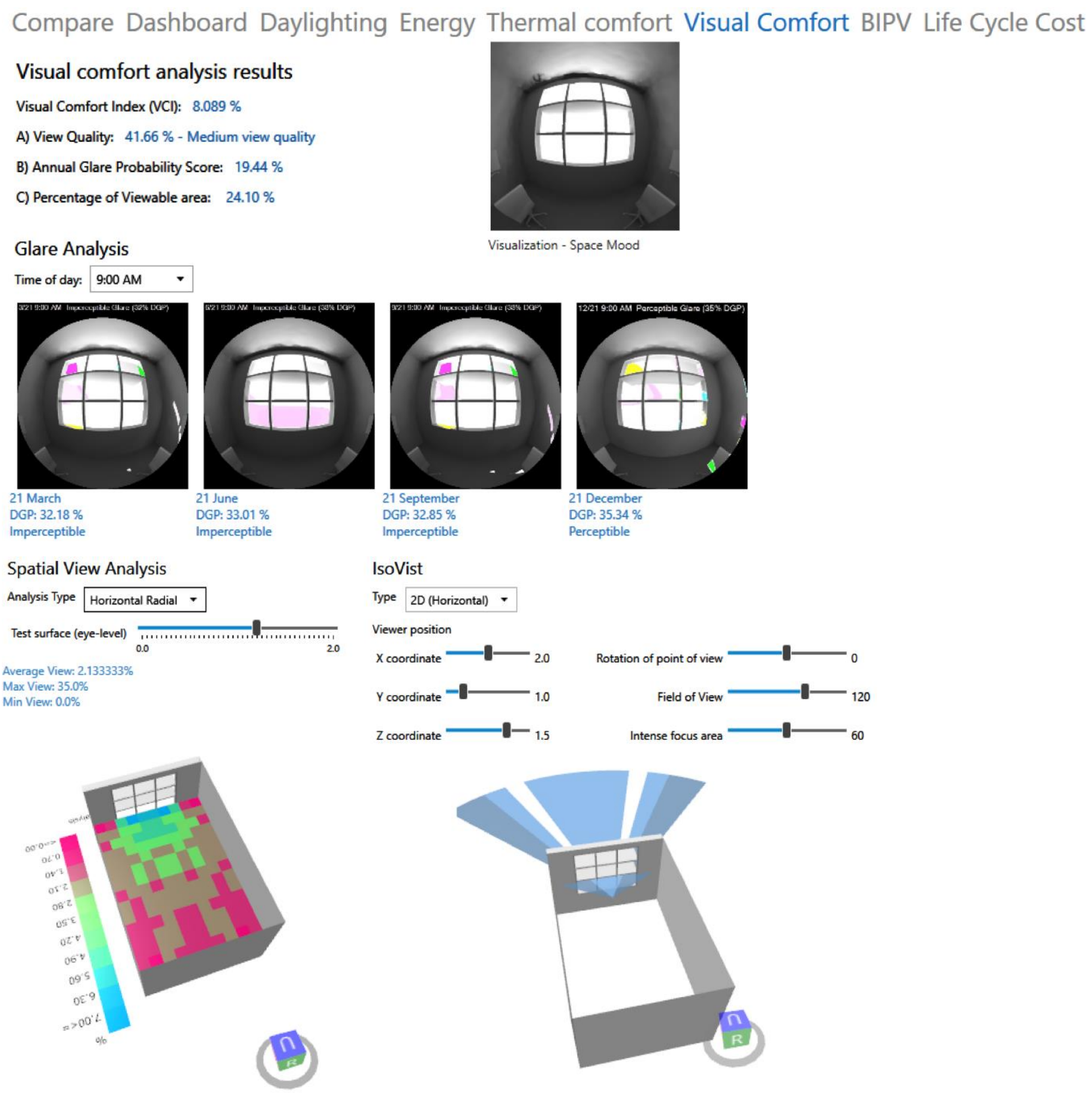
Screenshot of the energy tab in the integrated dashboard

Visual comfort

The visual comfort tab shows the results from the glare simulation and view analysis. In the summary part, it presents an interior rendering of the space to show the general ambient and mood of daylighting inside the space as well as the numerical results of each of the glare analysis as well as view quality and quantity. In the glare section, the user can see the results for the glare simulation in the form of fisheye renderings and numerical values, the user has the control to show the results for specific date and hour of the day when the simulation was conducted (Figure 6.4-7). In the view section, a spatial view analysis is presented to show how each point in the space performs regarding view-to-outdoor percentage. The eye-level can be controlled to mimic a setting or a standing person according to preference. A 2D and 3D isovist analysis is also provided for a specific point of interest inside the space (Figure 6.4-8). The point of interest is assigned by the user and can be chosen to resemble the position of workers. Usually, the viewpoint is the same used for the glare analysis, but other viewpoints can also be considered separately. The direction of view and the width of the view field can also be changed by the user. Finally, the view quality window can be opened from the tab and calculated the view quality according to the point system developed by Hellinga and Hordijk (2014), but can only be useful when more information about the project is available such as the context and surroundings of the building site. (Figure 6.4-9).

Figure 6.4-6

A screenshot of the glare and view sections from the Visual comfort tab.



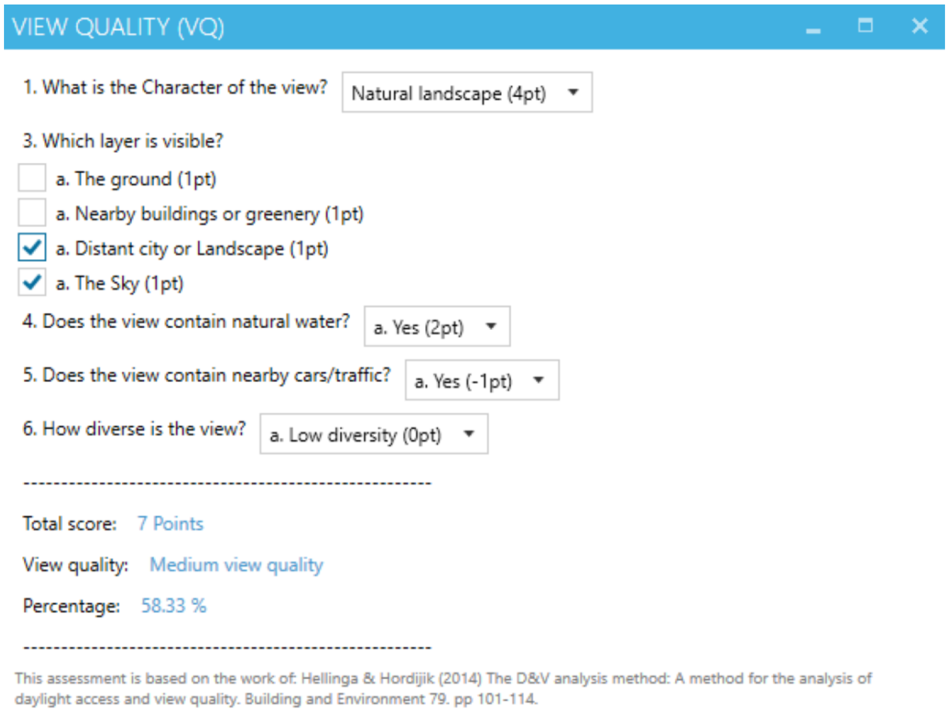


Figure 6.4-7

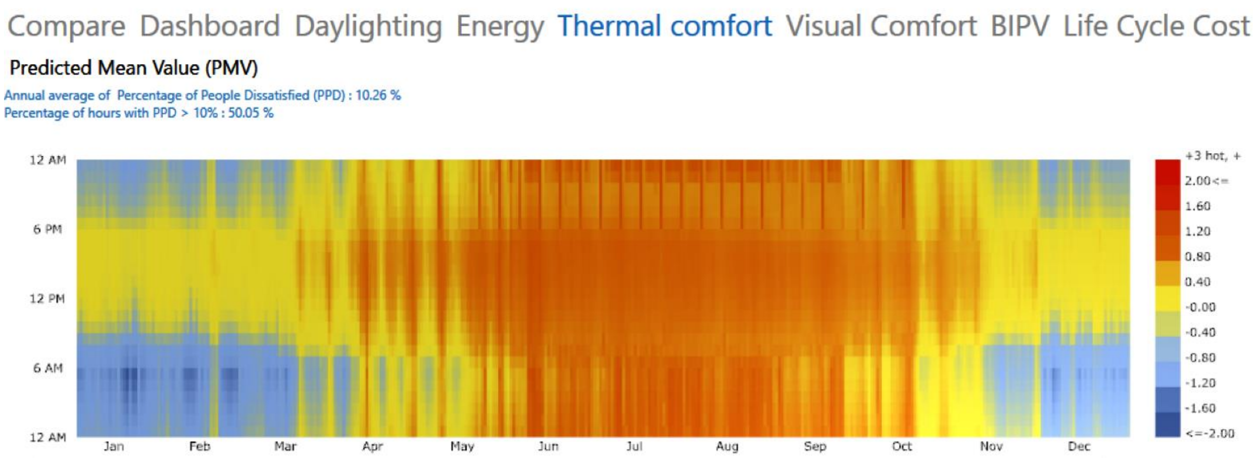
The view quality window with the point system originally developed by (Hellinga and Hordijk 2014).

Thermal comfort

In the thermal comfort section, the numerical results of the indoor thermal comfort calculations are presented. The PMV and PPD percentages are highlighted as well as a heat map for every hour in the year. The heat map helps the user in identifying the times and days of the year where it is most probably to be uncomfortable in the space and therefore take the right design decisions for these times. (Figure 6.4-10).

Figure 6.4-8

A screenshot of the thermal comfort tab from the integrated dashboard.



Energy generation

The energy generation or Building Integrated Photovoltaics (BIPV) tab shows the amount of energy that could be generated by covering the solid parts of the façade with PV cells. The total amount of annual AC and DC energy generated is displayed as well as the area that could be covered. The percentage of energy use offset by solar and a 3D visualization are provided.

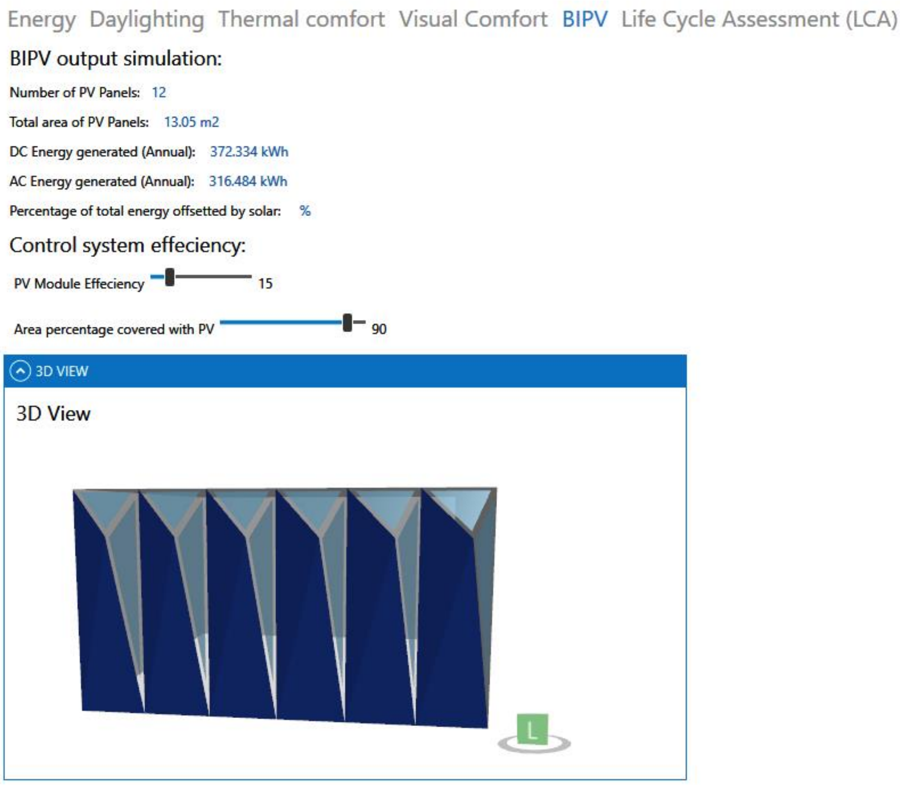


Figure 6.4-9

BIPV tab from the integrated dashboard

Life Cycle Assessment

The life cycle assessment is presented in terms of façade design material quantities and environmental impact using several aspects as discussed in Chapter 4. It worth noting that as most databases don't provide complete world-wide data for life cycle analysis, data for each type has to be entered by the user. The framework then calculates the area or the volume according to the type of material and provide the summation of the environmental impact of all the materials.

Figure 6.4-10

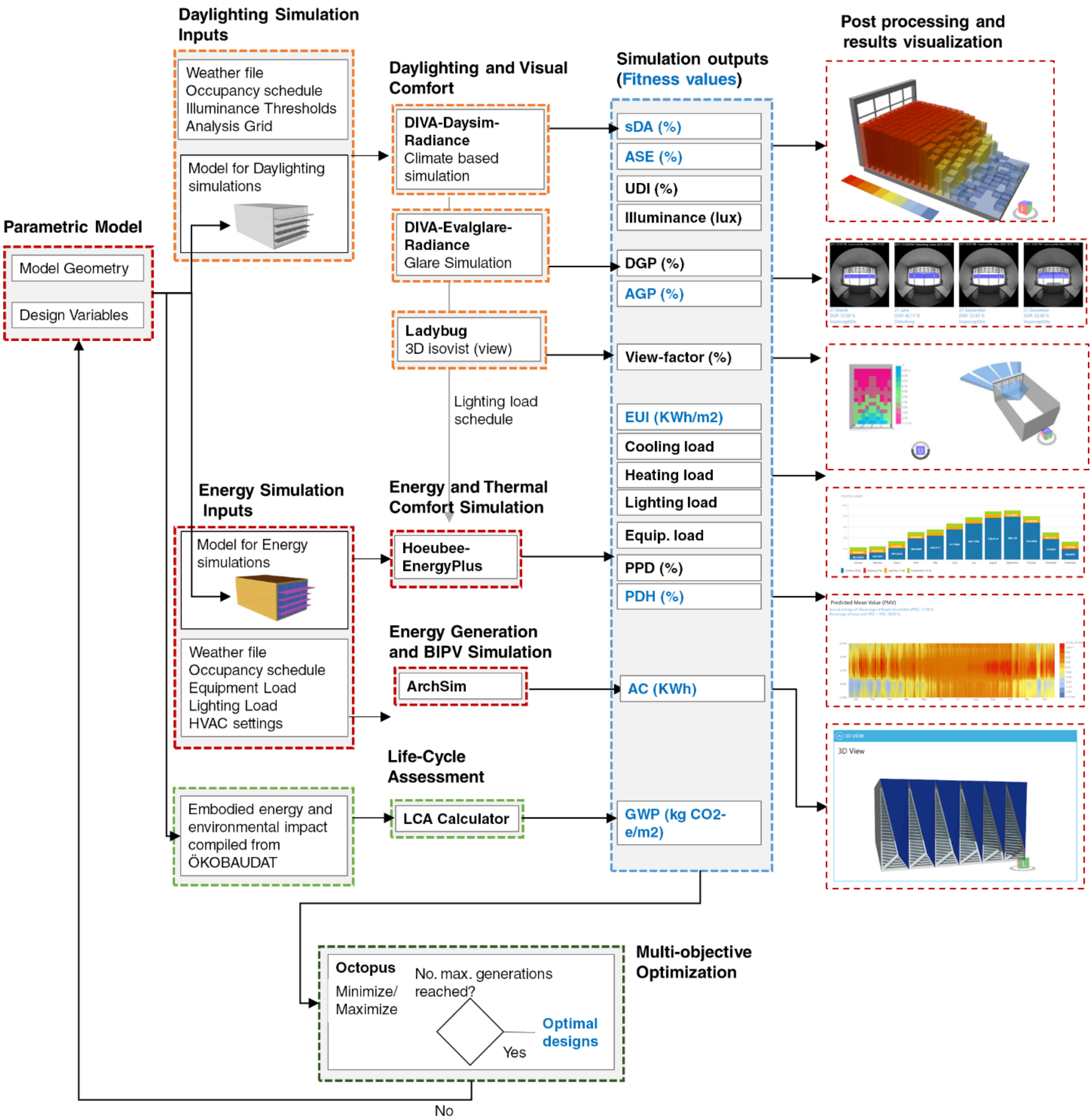
Life Cycle Assessment tab from the integrated dashboard.

6.5 Compatibility with the integrative performance optimization framework

The aim of the visualization tool is to enable designers and architects to get decision support information without the need to toggle between different tools and software package. That is why integrating the visualization tool with the main framework developed earlier in this study is essential. The visualization tool was built within the same ecosystem of grasshopper/Rhino software; therefore, it uses the same base as the framework. It can be used separately without the need for any 2D or parametric modeling. However, in this case, the user will be limited to specific pre-defined model parameters. Alternatively, with some knowledge of parametric modeling using grasshopper, the user can theoretically optimize any design and only use the framework and the visualization tool for the integrative optimization and data visualization. In both cases, the visualization tool functions seamlessly with the framework and can be considered as a part of the framework.

Figure 6.5-1

A conceptual diagram of the integrative performance optimization framework including the results visualizations



6.6 Conclusion and discussion

This chapter presents a prototype for a visualization tool that can help to analyze the results of building performance multi-objective optimizations. The visualization tool aids in investigating the whole design set, analyzing the relation between variables and objectives, as well as comparing and further investigating preferred designs. By achieving these different functions, the tool can help in the design decision process by shortening the time required to analyze the vast amount of data resulting from multi-objective optimization. In its current state the visualization dashboard is considered more as a proof-of-concept tool rather than a rigorous software program. In order for being more effective, the tool concept was presented to academics, researchers and professionals in focus groups and presentations in order to evaluate and further enhance the tool. The evaluation process is documented in the following chapter.

Chapter 7: Framework Evaluation

7.1 Introduction

The developed framework was validated during the development stage using case studies, which were discussed in Chapter 5. The main shortcoming was found in the need of using several tools to analyze and visualize the optimization and simulation results. In the previous chapter (Chapter 6), the framework was enriched by the addition of a design decision support and visualization tool. In this stage, the framework is further evaluated together with the visualization dashboard through two phases. In the first phase, the framework is introduced and presented to different-size groups of academics, researchers and professionals. The comments and suggestions from the participants were considered for further development in this chapter and also for future work. The framework was also communicated to a larger audience through three different publications (Gadelhak et al. 2017; Gadelhak and Lang 2016; Gadelhak and Wageh 2017), all of which are available online with open-access. In the second phase, a holistic case study is carried out to test and demonstrate the different functions of the updated framework.

7.2 Focus groups evaluations

Several focus groups were conducted with the aim to discuss the usability and shortcomings of the developed framework. Feedback and comments from the targeted groups were found notably helpful and aided in the further development of the framework and the design-decision-support tool. The focus groups were carried out in two different settings. The first set of focus group meetings consisted of a short presentation of fifteen minutes to demonstrate the framework, followed by open-ended questions to allow the participants to share their questions, comments, and suggestions. The users were asked to reflect on the tool and the possible areas of enhancements, that are important for a better usability and for delivering useful information for an informed decision-making process. The meetings took place in different places and contexts. The first focus group consisted of fifteen researchers and experts in the field of building simulation and sustainable design from the chair of energy efficient and sustainable building and design at the Technical University of Munich. The attendees were a mixture of PhD students and researchers in the field of architecture, civil engineering, and mechanical engineering. The second presentation was for a larger audience group with more experience in the specialty of Computer Aided Design, which occurred during the annual meeting and conference of the eCAADe association (Education and research in Computer Aided Architectural Design in Europe). The last focus group consisted of a mixed group of nearly fifty PhD students from the department of architecture with different academic and professional backgrounds. The aim of selecting the mentioned venues and focus groups was to ensure a diverse and wide spectrum of user representatives. In the second phase, one-to-one meetings were conducted with the interested users to try the tool and have a hands-on experience.

The most discussed suggestions for improvements and looked-for functions can be summarized as follows:

- Providing a simpler user interface and clearer visualizations for the simulation and optimization results.
- Provide a graphical presentation for the whole façade or building to better evaluate the esthetic aspect of the building façade.
- Provide more flexible design templates for complex parametric façade designs.
- Adding Life Cycle Cost (LCC) assessment as an important aspect when comparing design alternatives.

The focus groups suggestions were considered in the last version of the tool developed in this thesis. That included several updates in the framework and the parametric models as well as in the user interface and visualization techniques.

7.2.1 Updates to the visualization dashboard

Parametric models

The framework relies on a parametric modeling tool (Grasshopper) to ensure maximum flexibility and free-form design for building facades. However, as the framework also exports the model to different simulation engines, it is very critical to ensure the model's complexity doesn't affect the simulation process. In order to make it easier for inexperienced users, three modeling templates were provided to the user. By using these templates, the user can control all design parameters, as well as simulation and optimization settings without the need for any modeling experience. The chosen model templates were:

- A conventional façade with a solid wall construction and an opening. Variables in this template include the space dimensions, wall constructions, materials, and thickness; glazing type; shading; and daylight system types.
- A modular façade system which the user can define its module size, the solid and void surfaces as well as the different materials and construction types.
- A three-dimensional parametric facade that is based on the Schüco Parametric façade system (Schüco International KG 2015), which was used in the evaluation case study in this chapter.

The context and design parameters panel of the DDS tool changes according to the selected template.

User Interface

The visualization interface was redesigned to provide an interface that is more user-friendly. Similar to the interface described in Chapter 6, the interface consists of a control panel and a group of tabs. In the first tab, a graphical representation of the entire façade is shown so the user can examine the final shape and form of their building (Figure 7.2-1). Simulation and optimization results were grouped under different tabs in order not to confuse the user with much information in a single window. The Dashboard tab includes the result analysis and graphical representations for the simulation results (Figure 7.2-2), the Explore tab presents the optimization results (Figure 7.2-3), and he Compare tab provides a bar chart comparison between selected cases (Figure 7.2-4), while the variables-objectives relations can be generated from the Sensitivity tab (Figure 7.2-5).

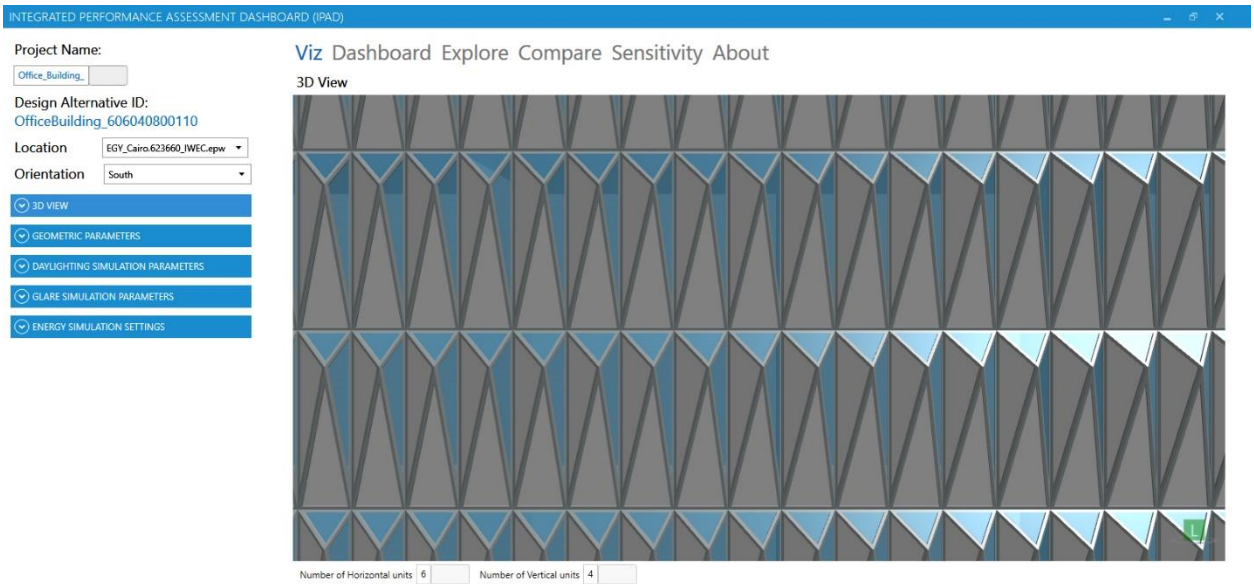


Figure 7.2-1

A screenshot of the Updated visualization tool.

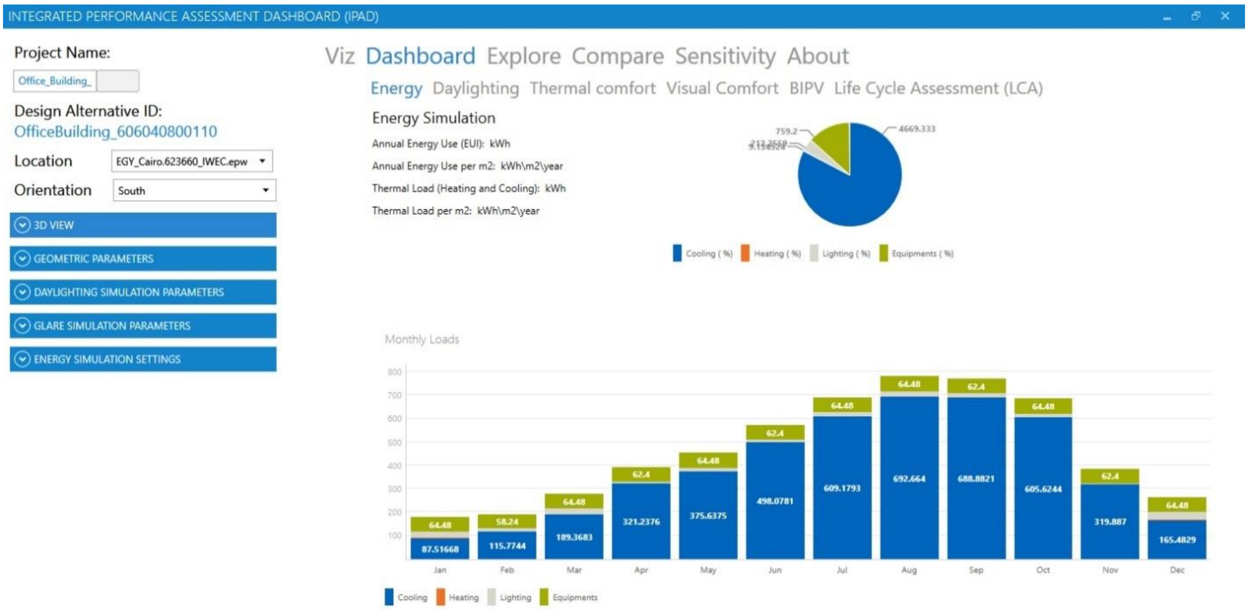


Figure 7.2-2

A screenshot of the Dashboard tab in the updated visualization tool.

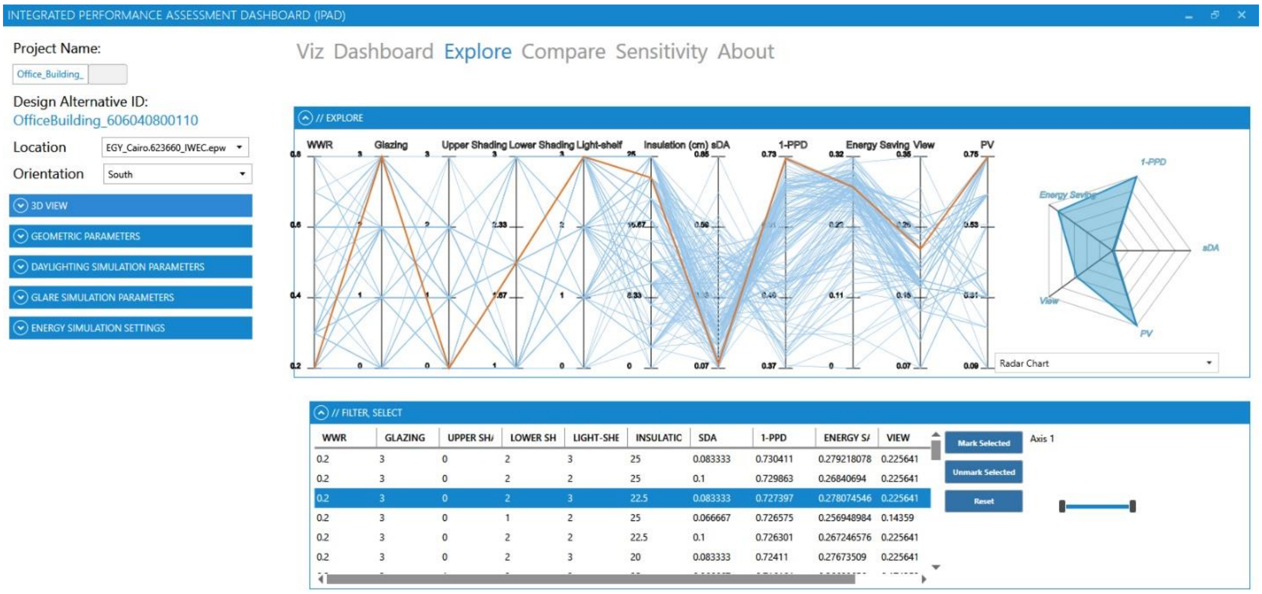


Figure 7.2-3

A screenshot of the Explore tab in the updated visualization tool.

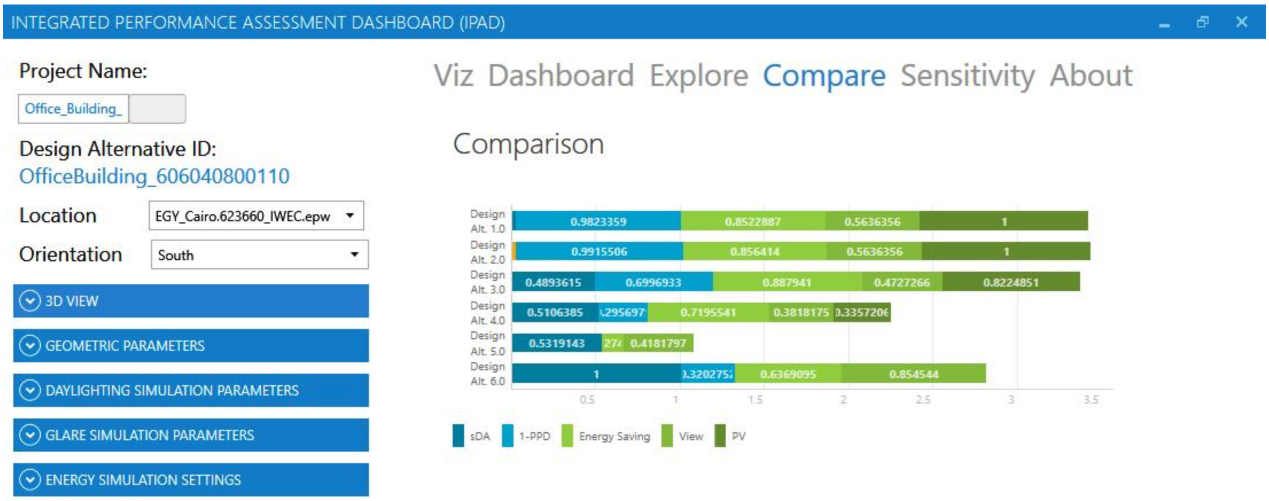


Figure 7.2-4

A screenshot of the Compare tab in the updated visualization tool.

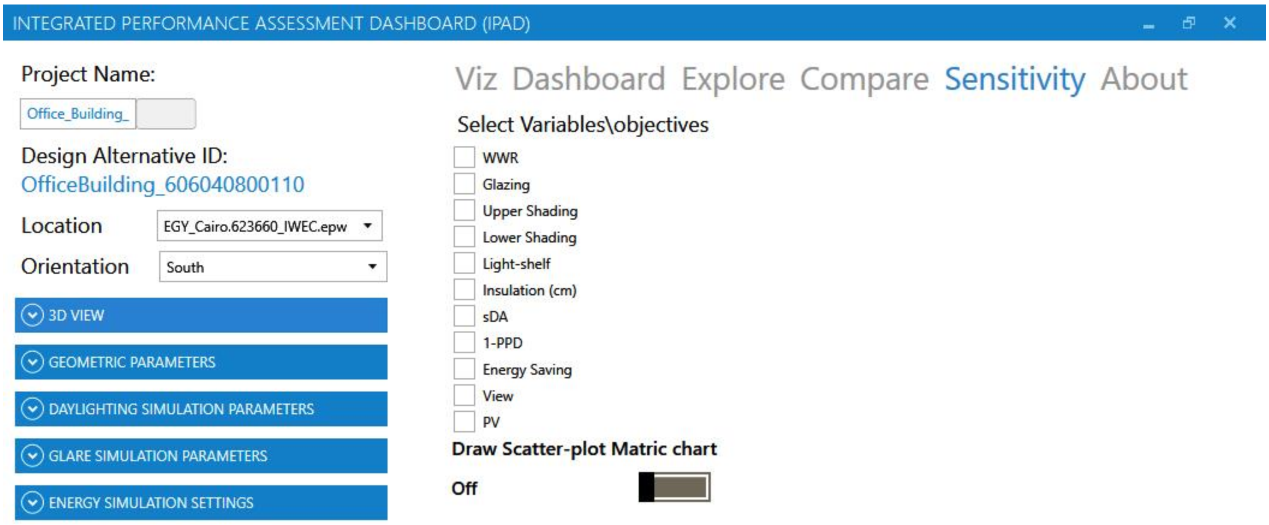


Figure 7.2-5

A screenshot of the Sensitivity tab in the updated visualization tool.

Life Cycle Cost

A cost estimator was also provided within the framework. The tool depends on manual inputs for each element unit price. The tool then calculates the number of units and amount of materials from the parametric model and multiply it by the unit cost to provide the initial cost. Energy unit cost can also be entered by the user to provide a simplified calculation for the operational cost in order to compare the Return on Investment (ROI) of different façade systems.

7.3 A holistic case study for a three-dimensional parametric façade system

A comprehensive case study was carried out to examine the framework with complex façade designs using an integrative performance assessment. In the case study, the façade of an office space, located in Munich, Germany, was optimized for the daylighting, energy use, visual comfort, thermal comfort, life cycle analysis as well as energy generation. The optimization was conducted for the four main orientations north, east, south, and west. Since the sun path is symmetrical the east and west orientations have almost identical performance in all studied aspect apart of the energy use and thermal comfort, therefore, only the east façade was studied. The east façade was chosen as it provides the worst-case scenario in both orientations, as the outdoor temperature can be higher at the afternoon, west façade has a higher thermal transfer, and therefore lower heating demand, which is dominant in the climate condition of Munich.

7.3.1 Parametric model and design approach

The space used in this study represents a typical side-lit office room that is 6 meters deep, 5.4 meters wide, and 3 meters high. The office room has a 3D curtain-wall façade based on the Schüco Parametric System (Schüco International KG 2015). The reason for choosing that particular system was to test the developed framework using a real-life complex system that represents the state-of-the-art in modern building technology. The system is also modular and provides a high degree of flexibility, which is a good example of parametric design. The Schüco parametric system is composed of three-dimensional modules with maximum dimensions of 1.5m x 4.0m. Each module consists of a highly thermally insulated aluminum frame with linear bars and connecting nodes, and a structural glazing with double or triple glazing. The nodes can be adjusted separately in the three-dimensions to provide maximum flexibility in the design.

Figure 7.3-1

The Schüco Parametric System.

Picture credits: Schüco International KG

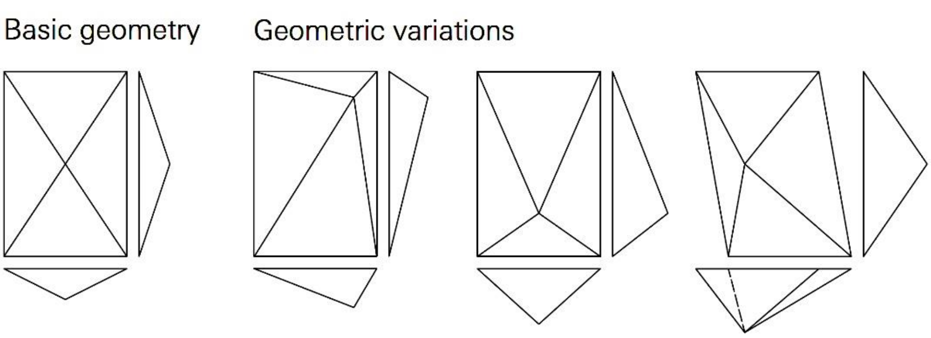


Figure 7.3-2

Rectangular module R2 system which will be used in this study,

Picture credits: Schüco International KG

Geometry

In this case study, more focus was put on the façade's geometry. The façade was divided into six modules, each module is 0.90m width and 3.00m high and consists of an aluminum frame and diagonal bars that intersect at a central point (node). The central point can be freely positioned in the X, Y and Z directions. The resulting geometry has four triangular surfaces for each module which can be either filled with a solid panel or a transparent glazing. (Figure 7.3-3).

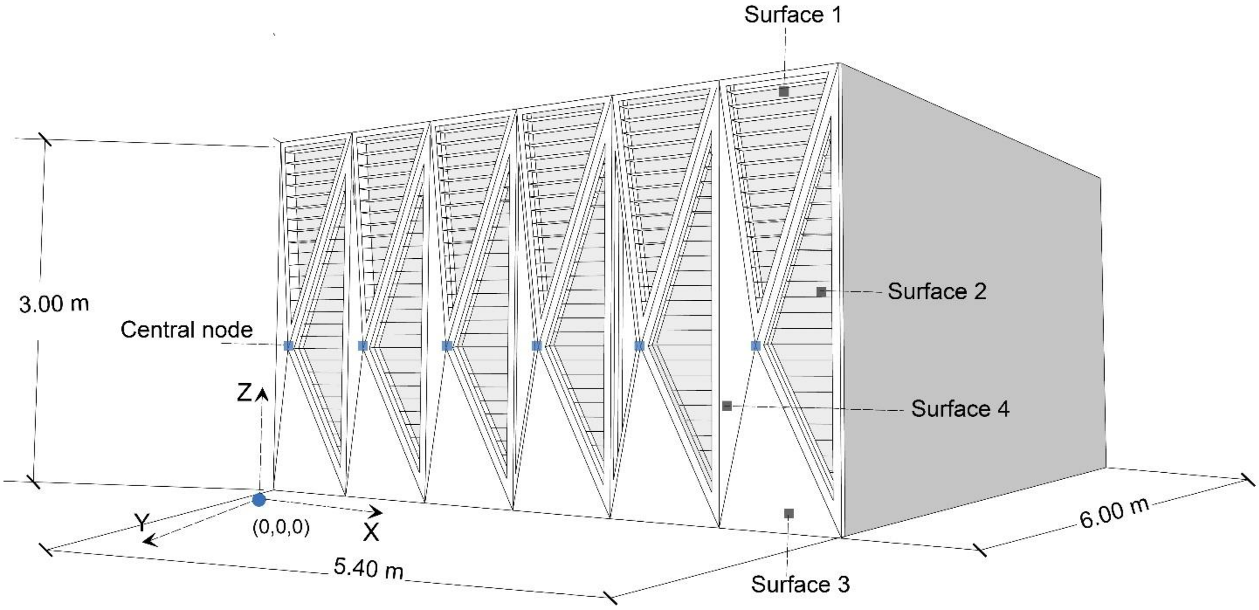


Figure 7.3-3

Three-dimensional representation of the parametric model.

Materials

The system was modeled with a highly thermal insulated aluminum façade with U-value of 0.384 W/m²K for solid panels and frame and 1.32 W/m²K for the double pane glazing. The addition of shading blinds on the glazing parts is possible. The following table presents the model materials and their daylighting and thermal properties. Table (7.3-1).

Table 7.3-1

The optical and thermal properties for the case study building materials.

Building element	Properties	
Frame	Thermal insulated aluminum frame	
Glazing	Double glazing (Low-E)	U-Value= 1.32 W/m2K
Solid panels	Fiber cement façade panel + 5 cm Mineral wool insulation + 2 cm Gypsum interior plaster	U-Value= 0.384 W/m2K
Ceiling	White colored with 80% reflectance; adiabatic	
Floor	Carpet floor with 20% reflectance; adiabatic	
External ground	Dark colored with 20% reflectance	
Furniture	Medium colored with 50% reflectance	

7.3.2 Simulation

A holistic numerical analysis was carried out for the daylighting, energy use, thermal comfort, visual comfort, as well as life cycle analysis and energy generation.

Daylighting simulation methodology

Similar to the methodology used in the previous case studies the daylighting performance was evaluated using spatial Daylight Autonomy (sDA) metric. Occupancy hours were assumed to be daily from 8 AM to 6 PM. The calculations were made for a reference plane of 90 measuring points in a grid of 0.60 m* 0.60 m, at a working-plane of 0.85 m height. Simulation parameters are shown in table (5.3-2). Cases with at least sDA 50% were considered acceptable, and cases with more than sDA 75% were preferred.

Table 7.3-2 Radiance simulation parameters

Ambient bounces	Ambient divisions	Ambient sampling	Ambient accuracy	Ambient resolution
4	1000	20	0.1	300

Energy simulation methodology

Energy simulations were conducted using EnergyPlus through the Ladybug+Honeybee plugin. The energy use for each design alternative was calculated hourly for the entire year for cooling, heating, lighting and equipment loads. The Energy use per floor area unit per year (EUI) was used to compare the efficiency of each design. All the surfaces of the tested office space were assumed adiabatic, except the external wall with the glazing. The detailed thermal properties are described in table (7.3-1). Equipment loads were assumed to be 8 W/m^2 and the lighting power density 11.8 W/m^2. Lighting load schedules and equipment load schedules were selected to be always on during the occupancy hours. During occupied hours, it is assumed that five people are present. The office space was considered to be fully air-conditioned and the HVAC cooling and heating setpoints were set at 24°C and 20°C respectively.

Thermal comfort methodology

Thermal comfort was evaluated using the Predicted Mean Value model (PMV). The PMV comfort calculator from the Ladybug+Honeybee plugin was used to calculate the Percentage of People Dissatisfied (PPD) for every hour over the entire year. Operative temperature, mean radiant temperature, and relative humidity were obtained from the energy simulation, while both metabolic rate and clothing level were set to 1 *met* and 1 *clo* respectively. Percentage of Discomfort Hours (PDH), which is the percentage of hours that had PPD more than 10%, was aimed to be minimized.

Visual comfort methodology

Glare and view analysis were conducted for a selective viewpoint that represents a seated person (height = 1.20 m), positioned at a distance of 2.00 m from the facade and facing the window. For glare analysis Evaglare was used to measure the discomfort using the Daylight Glare Probability (DGP) index. The DGP was analyzed at 9:00, 12:00 and 15:00 on the solstice and equinox dates to cover the different sun positions. In the DGP index, glare is divided into four categories: intolerable glare (DGP > 45%), disturbing glare (45% > DGP 40%), perceptible glare (40% > DGP 35%), and imperceptible glare (DGP < 35%). In this study, each category was given a score number with imperceptible glare having the highest score (3 pts) and intolerable glare the least (0 pts). The Annual Glare Percentage (AGP) is then calculated to compare the performance of the different designs, where the AGP = 0% means that no or only imperceptible glare occurs at all times and AGP = 100% indicates that an intolerable glare can be witnessed at all times. Acceptable cases were assumed to have a maximum of AGP = 50%. Cases with AGP less than 25% are preferred.

Life cycle assessment methodology

The amount of materials for each of the façade elements is calculated from the parametric model. Information of the environmental impact and embodied energy of each material were compiled from the ÖKOBAUDAT and documented in a CSV file. Table (7.3-3) shows the materials used in this case study and their corresponding LCA indicators values. A customized user component was then developed to extract this data and assign it to the corresponding material. For each LCA indicator, the amounts of each material were multiplied by its corresponding impact value. The resulting values were then added and divided by the total area of the façade as shown in equation (7.3-1). Finally, the values of each indicator were added and presented per meter square of the façade.

Table 7.3-3

Facade materials and its corresponding environmental impact.

Type	Material	Unit	PERT	PENRT	GWP	ODP	AP	EP
			[MJ]	[MJ]	[kg CO2-e]	[kg R11-e]	[kg SO_2-e]	[kg PO_4^{3}-e]
Facade structure	Aluminum frame profile	m	239.05	62.95	176.1	13.27	1.31E-10	0.062
Glazing	Insulated glazing, triple pane	m²	768.76	56.26	712.5	58.53	4.003E-11	0.241
Glazing	Insulated glazing, double pane	m²	477.93	33.03	444.9	37.47	2.373E-11	0.155
Glazing	Window glass, single	m²	133.706	7.406	126.3	10.13	5.079E-11	0.082
Sun protection	metal blinds	m²	422.43	93.13	329.3	24.31	2.028E-10	0.093
Cladding	Fiber cement facade panel	m²	138.52	58.28	80.24	7.199	3.236E-11	0.020
Insulation	Mineral wool (facade insulation)	m³	946.4	127.2	819.2	71.6	9.347E-11	0.336
Internal finish	Lime gypsum interior plaster	m³	1989.8	231.8	1758	196.6	1.618E-10	0.171

$$I_x = \frac{M_1X_1 + M_2X_2 + \cdots + M_nX_n}{A}$$

Equation 7.3-1
Total embodied environmental impact for each indicator.

Where:

I_x is the total impact of indicator x per area unit of the façade

M is the amount of the material

X is value of indicator x per material unit of material M

A is the total façade area

Energy generation

The maximum amount of possible energy generation was calculated by assuming the solid surfaces of the façade are covered with photovoltaics. Numerical simulations were made using Archsim, which is a part of the Diva-for-Rhino plugin. The plugin takes the panel geometry, panel efficiency and the effective area as inputs, and then executes an EnergyPlus simulation to calculate the energy generated annually. In this case study, panel efficiency was assumed to be 15% and the effective area as 90%. The sun position and panel orientation angles are considered in the calculations.

7.3.3 Optimization

Multi-objective optimization was performed using a Grasshopper's plug-in, Octopus, which is based on the evolutionary algorithm SPEA-2. It applies evolutionary principles to provide Pareto-optimal solutions. Design variables included the displacement of the central point of the façade modules in the X, Y, and Z directions, the material of the façade panels either fiber-cement façade panel or a double-glazing unit, and the existence or absence of solar shading. More details on the variables and the values and range for each variable are presented in table (7.3-4).

Table 7.3-4

Design variables of the optimization for this case study.

Design Variable	Type	Possible Values	No. of options
Displacement in X	Continuous	From 0.0 to 90.0 cm (15 cm step)	6
Displacement in Y	Continuous	From 0.0 to 100.0 cm (20 cm step)	6
Displacement in Z	Continuous	From 0.0 to 300.0 cm (50 cm step)	6
Surface 1 (upper-surface)	Discrete	Solid (fiber-cement panel) Void (double glazing)	2
Surface 2 (right-surface)	Discrete	Solid (fiber-cement panel) Void (double glazing)	2
Surface 3 (lower-surface)	Discrete	Solid (fiber-cement panel) Void (double glazing)	2
Surface 4 (left-surface)	Discrete	Solid (fiber-cement panel) Void (double glazing)	2
Shading	Discrete	Existent Non-existent	2
Total number of design alternatives			6,912

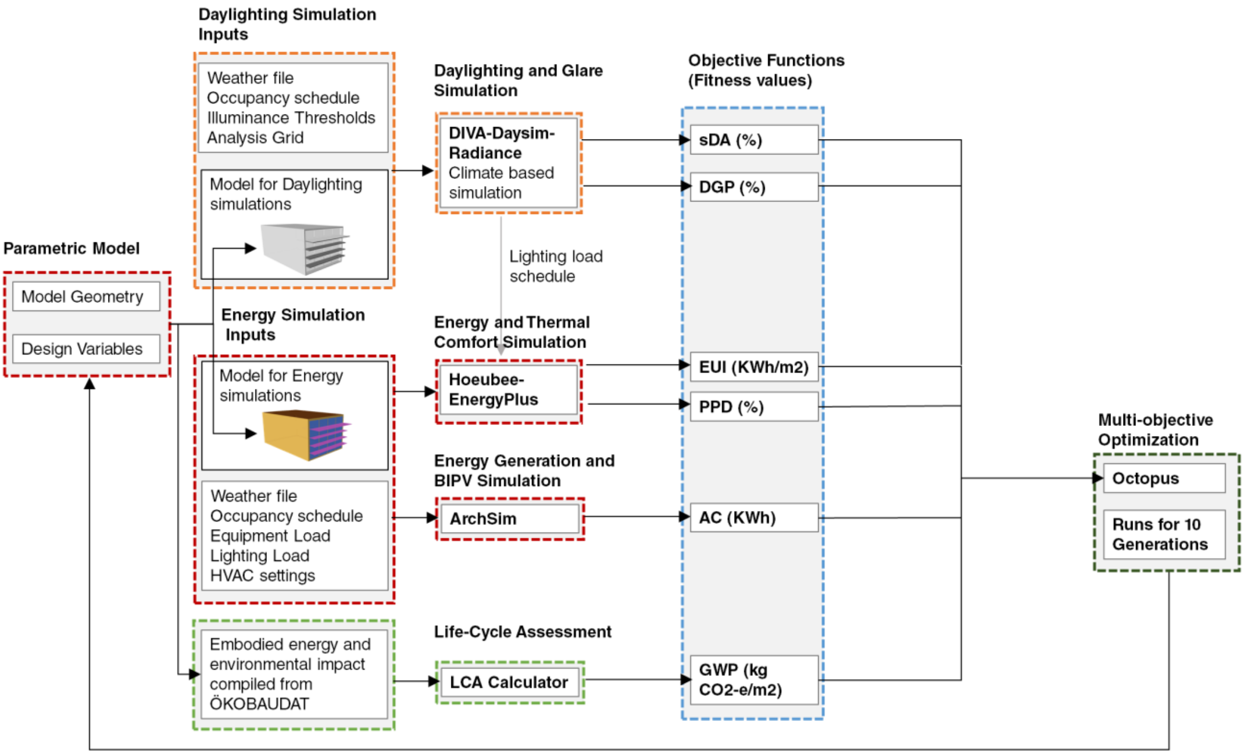
Six parameters were used as the objectives (fitness values) during the optimization process. The parameters were chosen to represent the aforementioned performance indicators:

- Daylighting performance: spatial daylight autonomy (sDA),
- Energy performance: Energy Use Intensity (EUI),
- Thermal comfort: Predicted Mean Vote (PMV),
- Visual comfort and glare: Disturbing Glare Probability (DGP),
- Life Cycle Assessment: Global Warming Potential (GWP),
- Energy generation: potential AC powered generated (AC).

For each orientation, the optimization process continues for 10 generations with a population size of 30. The mutation rate, mutation probability, and crossover were set to 0.5, 0.8, and 0.1 respectively. The optimization workflow is shown in figure (7.3-4). Results were then exported and analyzed using the developed framework.

Figure 7.3-4

Optimization process diagram



7.3.4 Optimization results

For each orientation, the optimization results were investigated in three consecutive steps. First, the optimization results were tabulated, sorted and filtered, then visualized with an interactive parallel coordinated graph using the explore tab in the IPAD tool, presented earlier in this chapter (Figure 7.2-3). The graph shows the values and range for each of the design variables and objectives. It provides a general idea on the performance range of the entire group of cases. In the second step, each performance aspect was studied separately to discover the cases that achieved the higher performance and the design variables that affected it. Finally, in the third step, the cases were filtered for only the ones that had acceptable and better performances in all aspects. The selected cases were compared by normalizing the results of each aspect using the normalization equation (6.4-2) as discussed in the previous chapter. The final selected cases are then presented with their full integrative assessment using the Compare and Dashboard tabs in the IPAD tool.

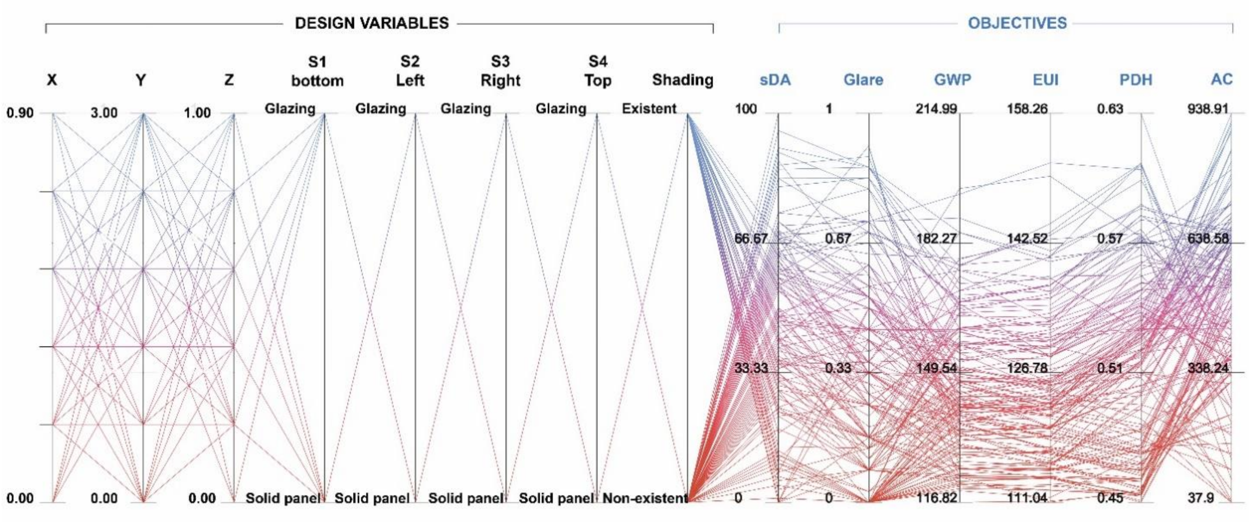
Optimization results for south orientation

Design space exploration

The optimization for the south façade resulted in 170 unique cases. The daylighting performance differed greatly between the cases and ranged between 0% and 100%. Fifty-nine cases achieved acceptable daylighting performance. The visual comfort performance of the cases also distributed over the entire scale. The majority of cases had an acceptable visual comfort condition, where almost half of the cases had imperceptible glare for more than 80% of the occupied time. Energy use reached a minimum of 111 kWh/m^2/year and had a maximum of 158 kWh/m^2/year. Nevertheless, thermal comfort showed a poor performance with a minimum of 45% PDH. Cases with more solid panels and fewer windows had an overall lower material embodied environmental impact. That is due to the fact that windows materials including the aluminum frame had a higher embodied environmental impact and their volume increases with the increase of the glass area. The energy generated had a very wide range as it extended between a minimum of 38 kWh/year and a maximum of 939 kWh/year. The detailed results of each performance aspect are discussed in the following sections.

Figure 7.3-5

The full spectrum of the optimization results for the south facing façade. The range and distribution of the cases for each objective are displayed.



Daylighting performance

Out of the 170 cases simulated, only one case reached the maximum of 100% sDA. Nevertheless, 59 cases had an acceptable daylighting performance. The existence of at least two glazing units, especially the top and one of the side panels, was found to have the biggest effect on daylighting performance. The position of the central node had a minor effect, which resulted in more options and diversity in the designs with acceptable performance. The existence of shadings reduced the daylight availability drastically and only six of the acceptable cases had shadings. Table (7.3-5) shows the cases with the highest daylighting performance.

Cases with the highest daylighting performance for the south orientation

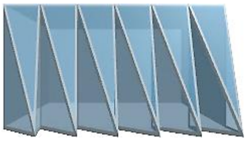
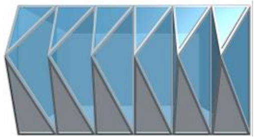
Façade Design			
Design Variables			
Displacement in X	0.90	0.00	0.15
Displacement in Y	1.00	0.80	0.80
Displacement in Z	0.00	0.50	0.50
Surface 1 (upper-surface)	Double-glazing	Double-glazing	Double-glazing
Surface 2 (right-surface)	Double-glazing	Double-glazing	Double-glazing
Surface 3 (lower-surface)	Fiber-cement panel	Fiber-cement panel	Fiber-cement panel
Surface 4 (left-surface)	Double-glazing	Fiber-cement panel	Fiber-cement panel
Shading	No shading	No shading	No shading
Daylighting Performance	**sDA= 100%**	**sDA= 95.6%**	**sDA= 91.1%**

Table 7.3-5

South façade designs, variables and daylighting performances for cases with the highest daylighting performance

Visual comfort

Most of the cases had an acceptable visual comfort and almost half of the cases had a preferable performance. However, cases with very low glare probability tend to have a lower or unacceptable daylight performance. Figure (7.3-6) shows the relation between the glare and daylighting performance. From the graph it can be noticed, that there is a proportional relation between the higher daylighting performance and the glare probability. This indicates the higher daylighting performance the case has, the less visual comfort it achieves. When considering only the cases with acceptable daylighting performance, four cases achieved favorable visual comfort, where no or only imperceptible glare occurs in more than 75% of the occupied times. Using an acceptance threshold of 50% of the time increased that number to 22 cases. In most acceptable cases, the central node was located in the middle of the façade unit giving a symmetrical look to the façade. Understandably, the least amount of glazing resulted in the least amount of glare. Nevertheless, a combination of a top and a side glazing unit was dominant in the cases that had acceptable daylighting and visual comfort performances. Table (7.3-6) shows the cases with the best visual comfort performance.

Table 7.3-6

South façade designs, variables and annual glare probability for cases with the highest visual comfort performance

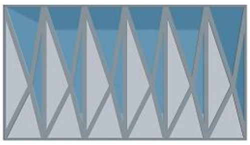
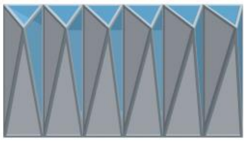
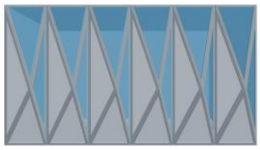
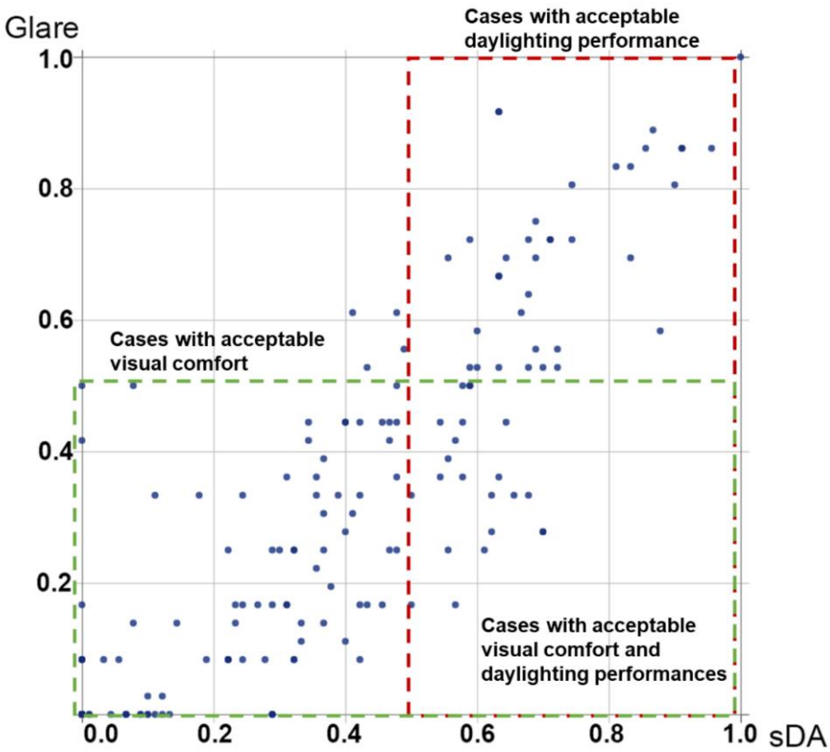
Cases with the highest visual comfort performance for the south orientation			
Façade Design			
Design Variables			
Displacement in X	0.45 m	0.45 m	0.45 m
Displacement in Y	0.00 m	0.60 m	0.20 m
Displacement in Z	1.50 m	2.50 m	1.50 m
Surface 1 (upper-surface)	Double-glazing	Double-glazing	Double-glazing
Surface 2 (right-surface)	Double-glazing	Double-glazing	Double-glazing
Surface 3 (lower-surface)	Fiber-cement panel	Fiber-cement panel	Fiber-cement panel
Surface 4 (left-surface)	Fiber-cement panel	Fiber-cement panel	Fiber-cement panel
Shading	No shading	No shading	No shading
Annual DGP (%)	**16.67%**	**16.67%**	**25%**

Figure 7.3-6

The relation between the spatial daylight autonomy (sDA) and the normalized annual daylight glare probability (DGP) of the south façade cases.



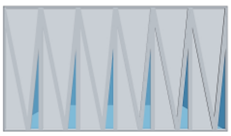
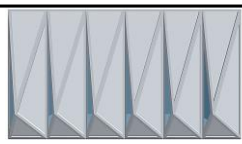
Energy performance

The energy use intensity ranged between 111 kWh/m2/year and 158 kWh/m2/year. Cases with lower energy consumption tended to have smaller glazing surfaces, and thus only one or two glazing surfaces. The equipment load was constant in all cases and the lighting load had minor changes. Nevertheless, together they represent a considerable amount of the total energy use. Given that Munich has an overall cold climate, the heating load was the main contributor to the change in the energy load. The minimum heating load was 31.5 kWh/m2/year, and the highest was more than double that value and reached 69 kWh/m2/year. Cases with the least energy use are shown in table (7.3-7).

Table 7.3-7

South façade designs, variables and energy use intensities for cases with the least energy consumption.

Cases with the highest energy performance for the south orientation

Façade Design			
Design Variables			
Displacement in X	0.45	0.45	0.15
Displacement in Y	0.00	0.80	0.20
Displacement in Z	0.00	1.00	0.50
Surface 1 (upper-surface)	Fiber-cement panel	Double-glazing	Fiber-cement panel
Surface 2 (right-surface)	Double-glazing	Fiber-cement panel	Fiber-cement panel
Surface 3 (lower-surface)	Na	Fiber-cement panel	Fiber-cement panel
Surface 4 (left-surface)	Fiber-cement panel	Fiber-cement panel	Double-glazing
Shading	No shading	No shading	No shading
Energy use intensity	**111.04 kWh/m2/year**	**111.17 kWh/m2/year**	**111.64 kWh/m2/year**

Thermal comfort

The percentage of people dissatisfied (PPD) exceeded the threshold (10%) for almost half of the occupied time in all cases. Although for most of the cases, the average of annual PPD was between 14-15% only, that is still considered unacceptable according to the ASHRAE recommendations (Standard 55-2010). Since most discomfort occurs due to the colder conditions during winter months, a probable solution to that is to use an efficient heating system or a dynamic solution

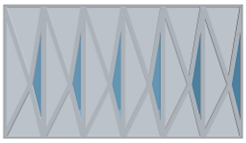
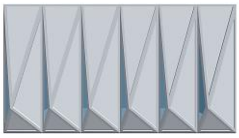
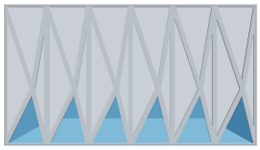
Life cycle assessment

The embodied environmental impacts of the building façade were driven by two main parameters. The total surface area of the façade and the number of glazing units. As a result, designs with less extruded geometry (smaller

Y-displacement) and middle, central position for the central node (middle X- and Z-displacements) had in general smaller amount of materials, and therefore smaller GWP. Moreover, since glass and aluminum had a higher environmental impact than other materials, designs with a smaller number and areas of glazing had less GWP.

Table 7.3-8

South façade designs, variables and global warming potential for cases with the lease embodied environmental impact.

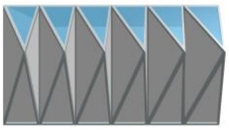
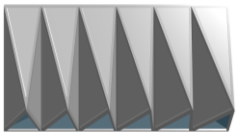
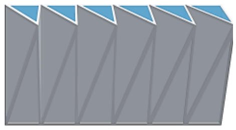
Cases with the lowest embodied environmental impact for the south orientation			
Façade Design			
Design Variables			
Displacement in X	0.45 m	0.15	0.45 m
Displacement in Y	0.00 m	0.20	0.00 m
Displacement in Z	1.00 m	0.50	1.00 m
Surface 1 (upper-surface)	Fiber-cement panel	Fiber-cement panel	Fiber-cement panel
Surface 2 (right-surface)	Double-glazing	Fiber-cement panel	Fiber-cement panel
Surface 3 (lower-surface)	Fiber-cement panel	Fiber-cement panel	Double-glazing
Surface 4 (left-surface)	Fiber-cement panel	Double-glazing	Fiber-cement panel
Shading	No shading	No shading	No shading
GWP/ façade area [kg CO2-e/m^2]	**119.82**	**119.73**	**120.28**

Energy generation

Similar to the environmental impact, energy generation was also driven by the same two parameters, the surface area and the number of surfaces with glazing units. However, while the surface area had to be minimized for a minimum environmental impact, it had to be maximized for higher energy generation. Nevertheless, similar to the case in LCA, lower number of glazing surfaces meant more areas for the PV units, and therefore more energy generation. The maximum energy generated for the period of one year reached a 939 kWh, which represents around 23.5% of the total annual energy consumption of the same design. In that case, only the relatively smaller top surface had a glazing unit which acted as a clear-story window, while all three other surfaces were solid.

Table 7.3-9

South façade designs and variables for cases with the highst energy generation potential.

Cases with the highest potential for energy generation for the south orientation			
Façade Design			
Design Variables			
Displacement in X	0.75	0.75	0.90
Displacement in Y	1.00	1.00	0.80
Displacement in Z	2.00	0.50	2.50
Surface 1 (upper-surface)	Double-glazing	Fiber-cement panel	Double-glazing
Surface 2 (right-surface)	Fiber-cement panel	Fiber-cement panel	Fiber-cement panel
Surface 3 (lower-surface)	Fiber-cement panel	Double-glazing	Fiber-cement panel
Surface 4 (left-surface)	Fiber-cement panel	Fiber-cement panel	Fiber-cement panel
Shading	No shading	No shading	No shading
Façade area that could be covered with PV units	**26.10 m²**	**23.70 m²**	**25.6 m²**
Potential AC energy	**938.912 kWh**	**914.354 kWh**	**902.632 kWh**

Optimal designs for south facing façade

It could be noticed from the previous sections how the design objectives conflict with each other. For instance, while the daylighting performance was enhanced by larger glazing surfaces, visual comfort and energy performance declined. Also, as the embodied environmental impact required smaller façade surface area, energy generation typically depended on a larger surface area for more PV modules. In some cases, however, some objectives may have similar tendencies in design results such as the tendency to have fewer glazing units in all objectives with the exception of the daylighting performance. To arrive at holistic optimal solutions and narrow down the selection group, the cases were filtered, using the Explore tool, to only those that were accepted in all aspects. As a result, 22 cases were chosen and then compared to each other using the Compare tab in the IPAD framework. The performance aspects were normalized and arranged with a descending order for the overall performance as shown in figure (7.3-7).

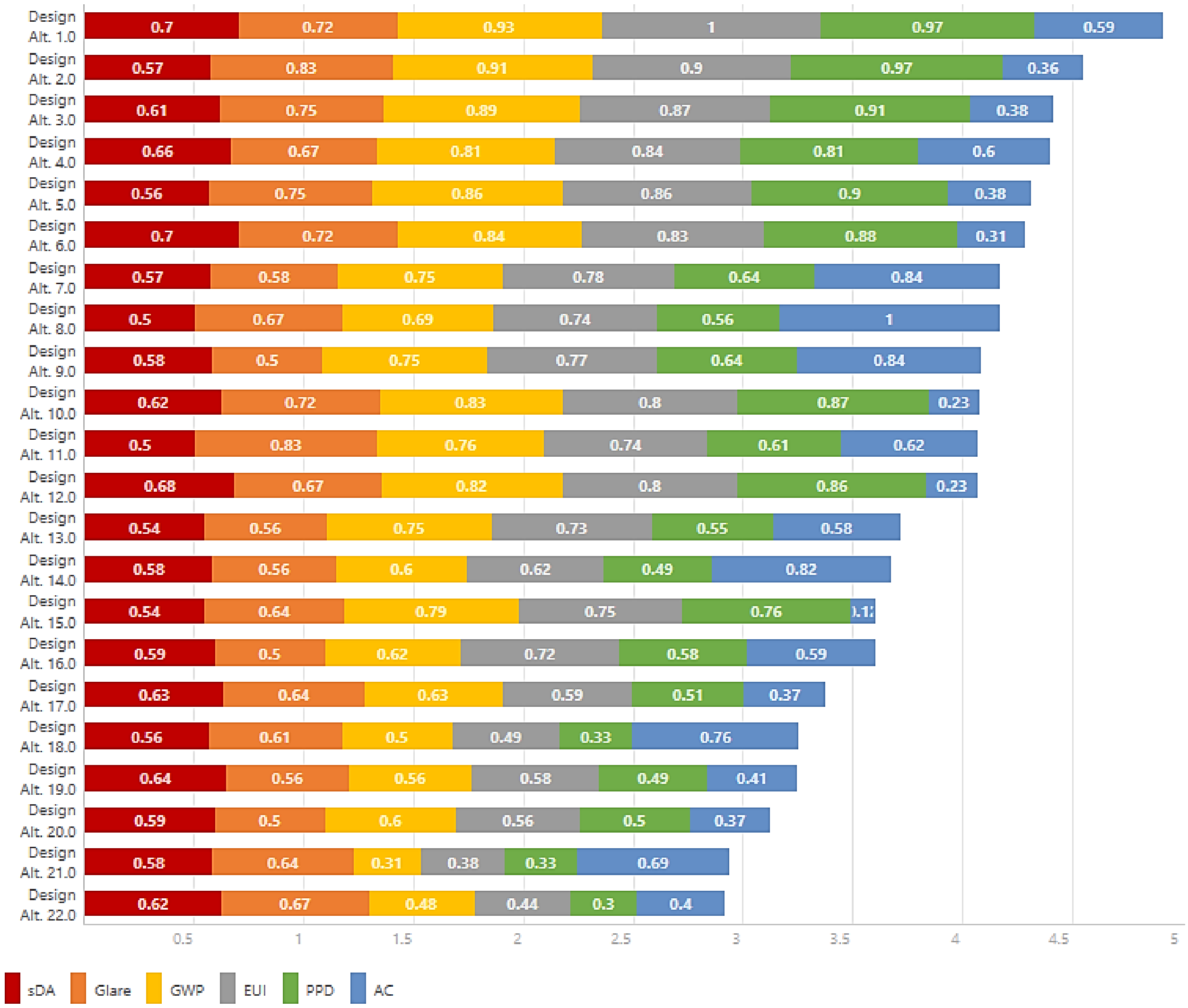


Figure 7.3-7

A comparison between the overall performance of the accepted cases for the south façade.

No specific values for design variables or trends were found dominant in the 22 cases. Designs with different central node positions as well as one, two or even three glazing units, achieved acceptable performance in all aspects. The comparison chart, shown above, aims to simplify the selection process by using a straightforward score-based method. While in real life situations some aspects may be more critical than others, in this case study, all performance aspects were given the same importance, and hence, the same weight. Nevertheless, it's important to always remember that each one of these scores represents a greater detail of information about the aspect it represents. The dashboard tab in the IPAD tool was used therefore for a quick but deeper investigation of each performance aspect. (Figure 7.3-8).

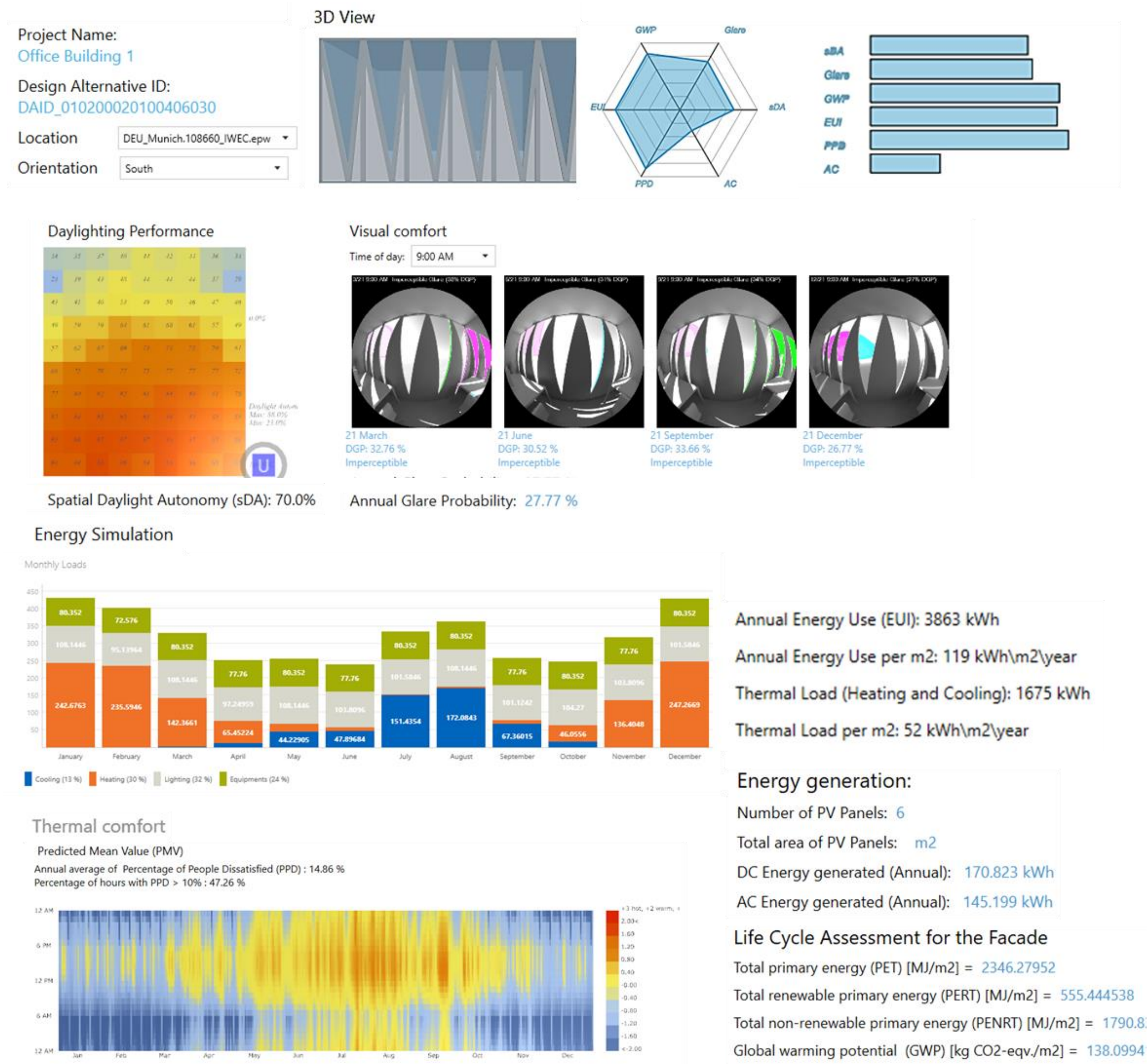


Figure 7.3-8

A screenshot for the summary section in the IPAD tool showing an overview of the integrative performance of façade with the highest performance in the south orientation

At the top of the dashboard general information about the case as well as a 3d representation and general performance radar and bar charts are shown. Below, visualizations for the simulation results for the daylighting, glare, energy use, thermal comfort are presented, as well as information about energy generation and embodied environmental impacts. The dashboard serves as a general performance report for each design, while more detailed information can be investigated in the separate tabs as discussed in chapter 6. In this case study, cases with highest overall performance were selected based on their overall score. The design variables and performance results of the five cases with the highest overall performance are shown in table (7.3-10). It can be noticed how diverse the optimal designs are, which accordingly gives the designer more options to choose from.

Table 7.3-10

Façade designs with the highest overall performance for the south orientation, and their corresponding design variables and performance. Values for the bar- and radar-charts are normalized.

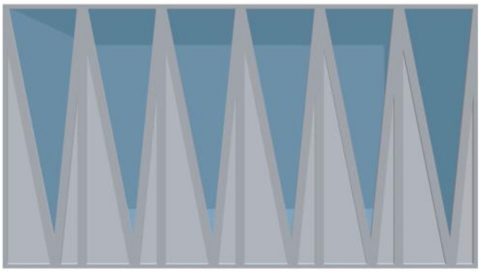
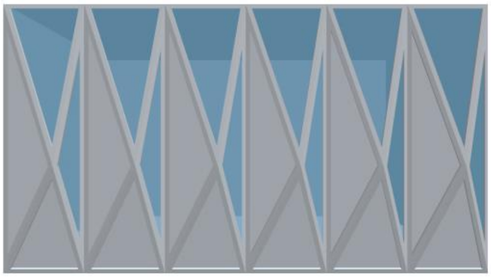
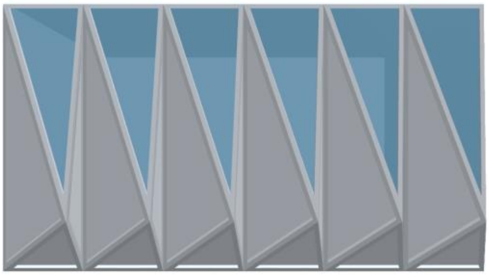
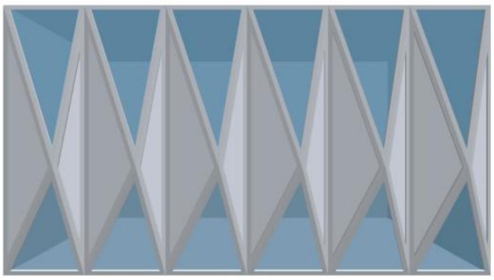
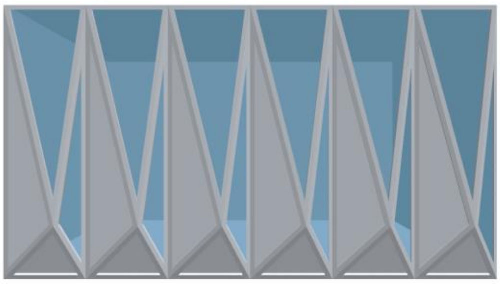
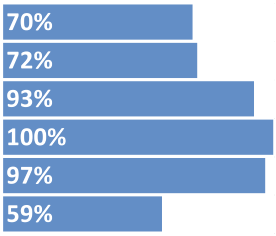
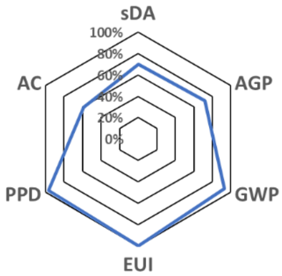
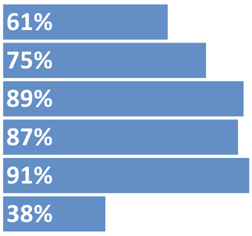
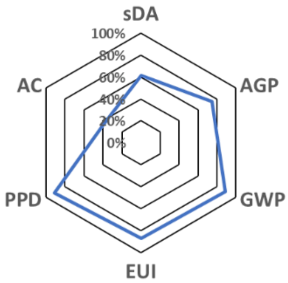
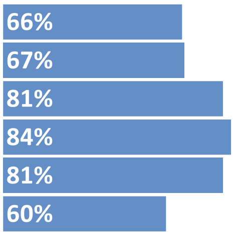
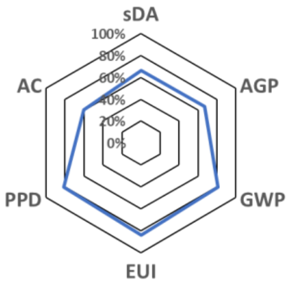
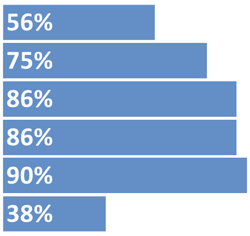
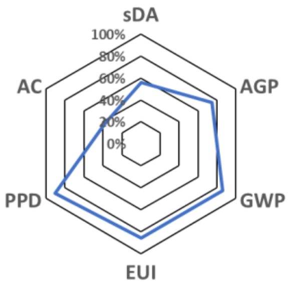
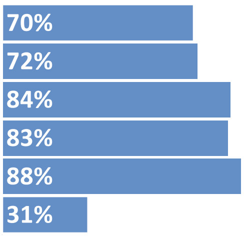
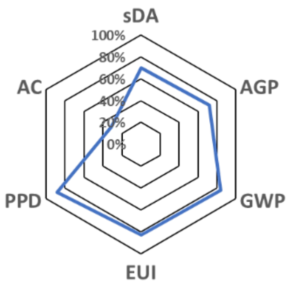
3D Visualization	Design variables	
	Displacement in X Displacement in Y Displacement in Z Upper surface Right surface Bottom surface Left surface Shading	0.45 m 0.00 m 0.00 m Fiber-cement panel Double-glazing Fiber-cement panel Fiber-cement panel No shading
	Displacement in X Displacement in Y Displacement in Z Upper surface Right surface Bottom surface Left surface Shading	0.45 m 0.20 m 1.00 m Double-glazing Double-glazing Fiber-cement panel Fiber-cement panel No shading
	Displacement in X Displacement in Y Displacement in Z Upper surface Right surface Bottom surface Left surface Shading	0.60 m 0.40 m 0.50 m Double-glazing Fiber-cement panel Fiber-cement panel Fiber-cement panel No shading
	Displacement in X Displacement in Y Displacement in Z Upper surface Right surface Bottom surface Left surface Shading	0.45 m 0.20 m 1.00 m Double-glazing Fiber-cement panel Double-glazing Fiber-cement panel No shading
	Displacement in X Displacement in Y Displacement in Z Upper surface Right surface Bottom surface Left surface Shading	0.45 m 0.20 m 0.50 m Double-glazing Double-glazing Fiber-cement panel Fiber-cement panel No shading

Table 7.3-10 (continued)

Objectives performances	Bar-chart	Radar-chart
	(Normalized values, higher values indicate better performance)	
sDA 70% [%] AGP 28% [%] GWP 132.40 [kg CO2-e/m2] EUI 119.14 [kWh/m2/year] PPD 47% [%] AC 317.21 [kWh]		
sDA 61% [%] AGP 25% [%] GWP 127.98 [kg CO2-e/m2] EUI 117.39 [kWh/m2/year] PPD 47% [%] AC 381.69 [kWh]		
sDA 66% [%] AGP 33% [%] GWP 135.41 [kg CO2-e/m2] EUI 118.74 [kWh/m2/year] PPD 49% [%] AC 575.57 [kWh]		
sDA 56% [%] AGP 25% [%] GWP 130.26 [kg CO2-e/m2] EUI 117.79 [kWh/m2/year] PPD 47% [%] AC 377.07 [kWh]		
sDA 70% [%] AGP 28% [%] GWP 132.40 [kg CO2-e/m2] EUI 119.14 [kWh/m2/year] PPD 47% [%] AC 317.21 [kWh]		

Optimization results for east orientations

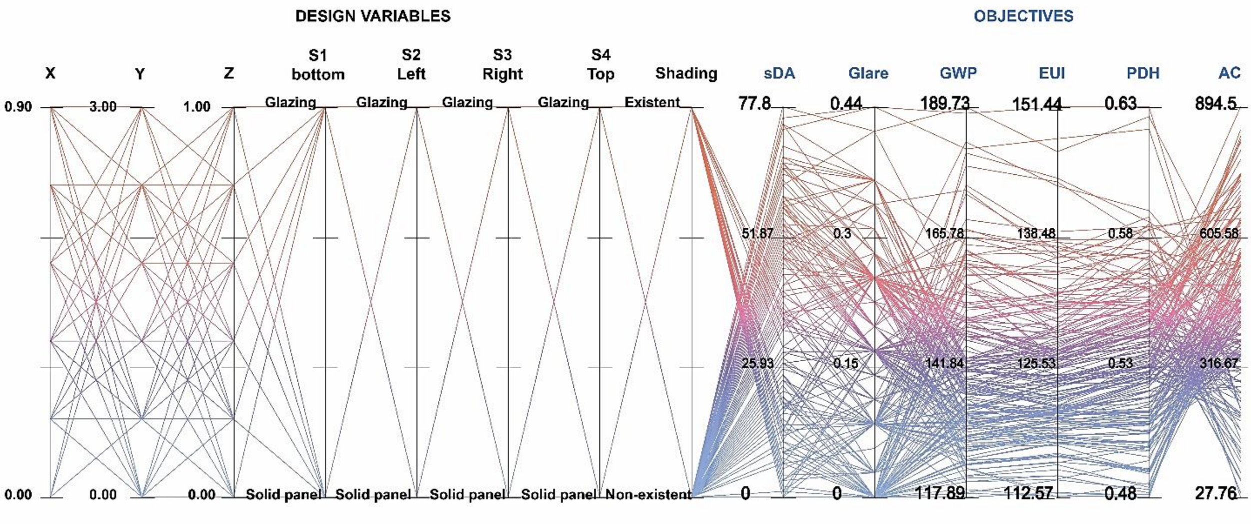
As mentioned at the beginning of the case study, only east façade was considered as the due to the almost identical performance to the west faced in many aspects and having a more critical thermal comfort condition.

Design space exploration

Altogether, 212 unique cases were obtained from the optimization process. Sixty-three cases had an acceptable daylighting performance, but just two cases had the preferred daylighting performance (sDA>75%). The spatial daylight autonomy reached a maximum of 77.8%. All the cases were found to have an acceptable visual comfort, where most of the cases (184 cases) had an imperceptible glare for more than 75% of the occupied time. Energy use intensity ranged between a minimum of 112 kWh/m2/year and a maximum of 151.4 kWh/m2/year. Similar to the south façade, the thermal comfort was found to have an unacceptable performance in most cases. Only 31 cases had a PDH less than 50% with a minimum PDH of 48%. Embodied environmental impact, represented by the total global warming potential of the façade materials, ranged between 118 and 190 Kg CO_2-e/m^2. The potential of the annual energy generation ranged between 28 and 895 kWh. Figure (7.3-9) shows the full range for the design variables and objectives of the studied designs.

Figure 7.3-9

The full spectrum of the optimization results for the east facing façade. The range and distribution of the cases for each objective are displayed.



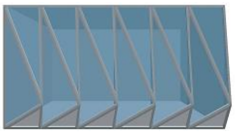
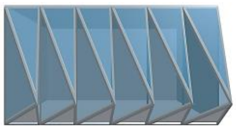
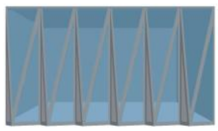
Daylighting performance

62 cases achieved an acceptable daylighting performance of sDA 50%. However, only two cases had a favorable performance (sDA ≥ 75%). Since the spatial daylight autonomy is a quantitative metric and doesn't take in

consideration of over-lit spaces, cases with more glazing units (two and three) tended to have an overall better performance as these cases receive more daylight. That, of course, is in conflict with the visual and thermal comfort. However, unlike the south orientation, cases with high daylighting performance had also acceptable visual comfort. Table (7.3-11) shows the cases with the highest spatial daylight autonomy.

Table 7.3-11

East façade designs, variables and daylighting performances for cases with the highest daylighting performance

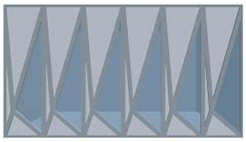
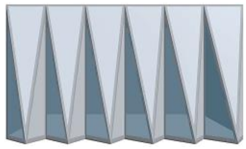
Cases with the highest daylighting performance for the east orientation			
Façade Design			
Design Variables			
Displacement in X	0.90 m	0.90 m	0.15 m
Displacement in Y	0.20 m	0.80 m	0.20 m
Displacement in Z	0.50 m	0.50 m	0.00 m
Surface 1 (upper-surface)	Double-glazing	Double-glazing	Double-glazing
Surface 2 (right-surface)	Fiber-cement panel	Fiber-cement panel	Double-glazing
Surface 3 (lower-surface)	Fiber-cement panel	Fiber-cement panel	Fiber-cement panel
Surface 4 (left-surface)	Double-glazing	Double-glazing	Fiber-cement panel
Shading	No shading	No shading	No shading
sDA (%)	**77.8 %**	**75.6 %**	**74.4 %**

Visual comfort

The annual glare percentage ranged between 0% and 44%, which is relatively much better performance than that of the south-facing facades. A considerable amount of cases had almost no glare occurrence at all, and most cases (184 cases) had imperceptible or no glare for more than 75% of the occupied time. The cases with the best visual comfort had, however, very limited glazing areas which doesn't allow sufficient daylight. Table (7.3-12) shows the cases with the least annual glare percentage.

Table 7.3-12

East façade designs, variables and annual glare probability for cases with the highest visual comfort performance

Cases with the highest visual comfort performance for the east orientation			
Façade Design			
Design Variables			
Displacement in X	0.15 m	0.30 m	0.45 m
Displacement in Y	0.00 m	0.40 m	0.80 m
Displacement in Z	0.50 m	2.50 m	0.00 m
Surface 1 (upper-surface)	Fiber-cement panel	Fiber-cement panel	Fiber-cement panel
Surface 2 (right-surface)	Double-glazing	Fiber-cement panel	Fiber-cement panel
Surface 3 (lower-surface)	Fiber-cement panel	Fiber-cement panel	Fiber-cement panel
Surface 4 (left-surface)	Fiber-cement panel	Double-glazing	Double-glazing
Shading	No shading	No shading	No shading
Annual DGP (%)	**0 %**	**0 %**	**25%**

Energy performance

Energy consumption ranged between 112.6 and 151.4 kWh/m2/year. Similar to the south façade, energy consumption increased with the increase in the glazing area. Less extruded, or almost two-dimensional facades were found to have better performance, as well as the facades with fewer and smaller windows. Nonetheless, in some cases that had larger glazing area, shading devices were also found to improve energy performance.

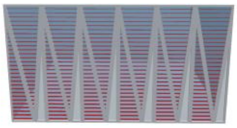
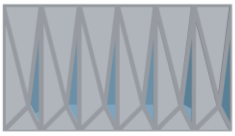
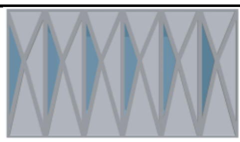
Thermal comfort

The indoor thermal comfort had an overall performance similar to that of the south façade. The average percentage of people dissatisfied over the entire year ranged between 15 and 21%, exceeding the threshold of 10%. Moreover, more than 10% of the occupants had undesirable indoor thermal comfort for almost half of the occupied time. Similar to the energy performance, cases with smaller surface area and less glazing units had a slightly better performance. As a result, cases with the least EUI were found to also have the least PDH. Cases with the least energy use intensity and PDH are presented in table (7.3-13).

Table 7.3-13

East façade designs, variables and their corrosponding energy use intensities and thermal comfot for cases with the least energy consumption.

Cases with the highest energy and thermal comfort performance for the east orientation

Façade Design			
Design Variables			
Displacement in X	0.45 m	0.45 m	0.30 m
Displacement in Y	0.00 m	0.00 m	0.00 m
Displacement in Z	0.00 m	0.50 m	2.00 m
Surface 1 (upper-surface)	Double-glazing	Fiber-cement panel	Fiber-cement panel
Surface 2 (right-surface)	Fiber-cement panel	Double-glazing	Fiber-cement panel
Surface 3 (lower-surface)	NA	Fiber-cement panel	Fiber-cement panel
Surface 4 (left-surface)	Double-glazing	Fiber-cement panel	Double-glazing
Shading	Horizontal blinds	No shading	No shading
Energy use intensity	**112.6 kWh/m2/year**	**113 kWh/m2/year**	**114.3 kWh/m2/year**
Average annual PPD	**15%**	**15%**	**15%**

Life cycle assessment

Since embodied environmental impact is not dependent on the orientation, it's self-explanatory that the same observations and cases with the best performance for the south façade also apply to all orientations.

Energy generation

The overall energy generation was found to be less than that of the southern façade. Similar tendencies of larger extrusion and side surfaces to capture low sun rays were noticed. The maximum energy generation reached 894.5 kWh, which represents about 22% of the energy use of the same case.

Optimal designs for east facing façade

Overall, 63 cases were found to have an acceptable performance. However, the overall performance was found to be inferior to that of the south façade. The design variables and performance results of the five cases with the highest overall performance is shown in table (7.3-14). In most cases, a top glazing was sufficient to provide enough daylight without much sacrifice on other aspects. In many cases, however, two and three glazing units also exist.

Table 7.3-14

Facade designs with the highest overall performance for the east orientation, and their corresponding design variables and performance. Values for the bar- and radar-charts are normalized.

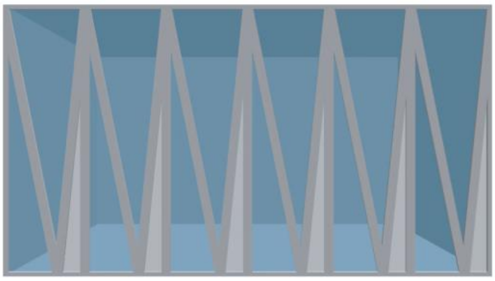
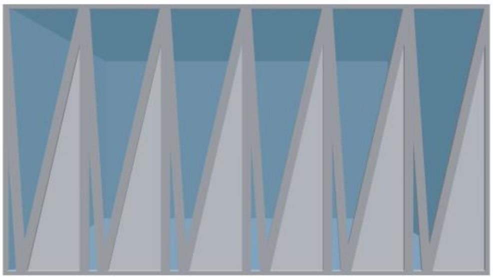
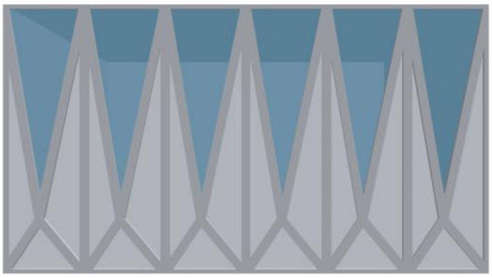
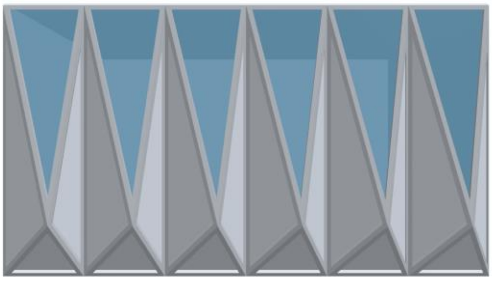
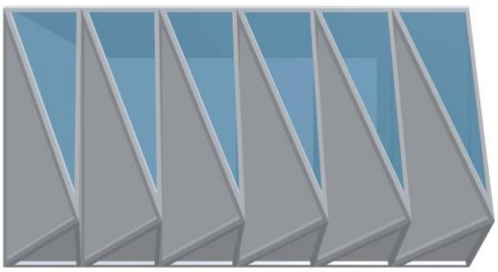
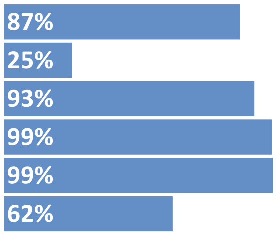
3D Visualization	Design variables	
	Displacement in X	0.45 m
	Displacement in Y	0.00 m
	Displacement in Z	0.00 m
	Upper surface	Double-glazing
	Right surface	Fiber-cement panel
	Bottom surface	NA
	Left surface	Double-glazing
	Shading	No shading
	Displacement in X	0.15 m
	Displacement in Y	0.00 m
	Displacement in Z	0.00 m
	Upper surface	Double-glazing
	Right surface	Fiber-cement panel
	Bottom surface	NA
	Left surface	Double-glazing
	Shading	No shading
	Displacement in X	0.45 m
	Displacement in Y	0.00 m
	Displacement in Z	0.50 m
	Upper surface	Double-glazing
	Right surface	Fiber-cement panel
	Bottom surface	Fiber-cement panel
	Left surface	Fiber-cement panel
	Shading	No shading
	Displacement in X	0.60 m
	Displacement in Y	0.40 m
	Displacement in Z	0.50 m
	Upper surface	Double-glazing
	Right surface	Fiber-cement panel
	Bottom surface	Fiber-cement panel
	Left surface	Fiber-cement panel
	Shading	No shading
	Displacement in X	0.90 m
	Displacement in Y	0.60 m
	Displacement in Z	0.20 m
	Upper surface	Double-glazing
	Right surface	Fiber-cement panel
	Bottom surface	Fiber-cement panel
	Left surface	Fiber-cement panel
	Shading	No shading

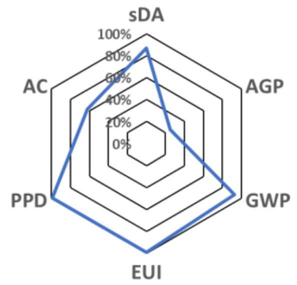
Table 7.3-14 (continued)

Objectives performances | **Bar-chart** | **Radar-chart**

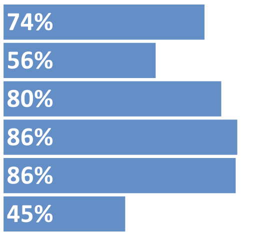
(Normalized values, higher values indicate better performance)

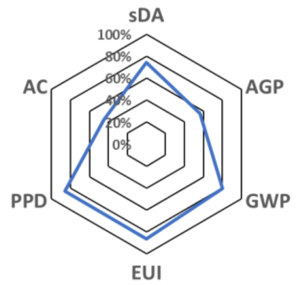
sDA	68%	[%]
AGP	33%	[%]
GWP	123.26	[kg CO2-e/m2]
EUI	112.90	[kWh/m2/year]
PPD	48%	[%]
AC	568.55	[kWh]



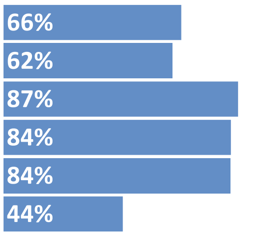


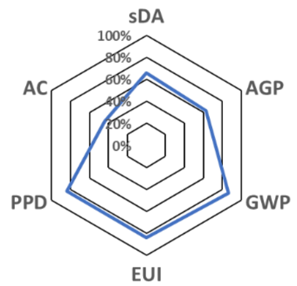
sDA	58%	[%]
AGP	19%	[%]
GWP	132.01	[kg CO2-e/m2]
EUI	117.88	[kWh/m2/year]
PPD	50%	[%]
AC	416.94	[kWh]



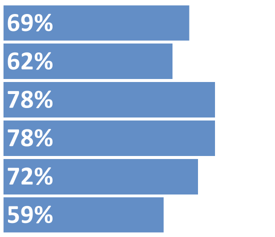


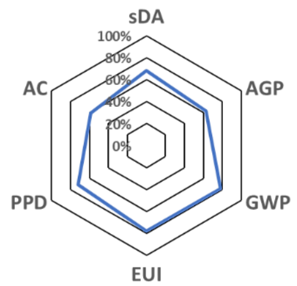
sDA	51%	[%]
AGP	17%	[%]
GWP	127.50	[kg CO2-e/m2]
EUI	118.73	[kWh/m2/year]
PPD	50%	[%]
AC	409.36	[kWh]



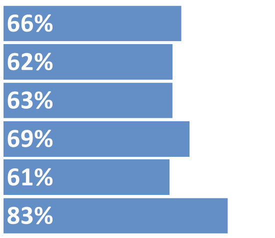


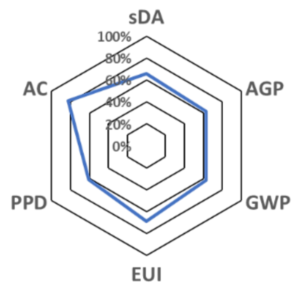
sDA	53%	[%]
AGP	17%	[%]
GWP	133.52	[kg CO2-e/m2]
EUI	121.06	[kWh/m2/year]
PPD	52%	[%]
AC	540.29	[kWh]





sDA	51%	[%]
AGP	17%	[%]
GWP	144.80	[kg CO2-e/m2]
EUI	124.77	[kWh/m2/year]
PPD	54%	[%]
AC	744.65	[kWh]





Optimization results for north orientation

Design space exploration

An overall of 196 unique designs resulted during the optimization process. The daylighting performance ranged between sDA 0% and 70%. Understandably as much less sunlight is available at north façade, the overall daylighting performance was less than that at the south and east facades. Visual comfort, however, was much better as almost all cases had no glare. The AGP was found to be 0% for most of the cases and reached a maximum of 16.67%. Energy consumption had a minimum of 111.6 kWh/m2/year and a maximum of 160 kWh/m2/year. Thermal comfort was slightly worse than that of the south and east facades, with a minimum PDH of 49% and a maximum of 61%. Embodied environmental impact ranged between GWP 116.5 and 207 Kg CO2-e/m^2. The potential of annual energy generation was also understandably much lower than that of a south or east façade and ranged between 485.6 kWh and a minimum of just 21 kWh. Figure (7.3-10) shows the full range for the design variables and objectives of the studied designs.

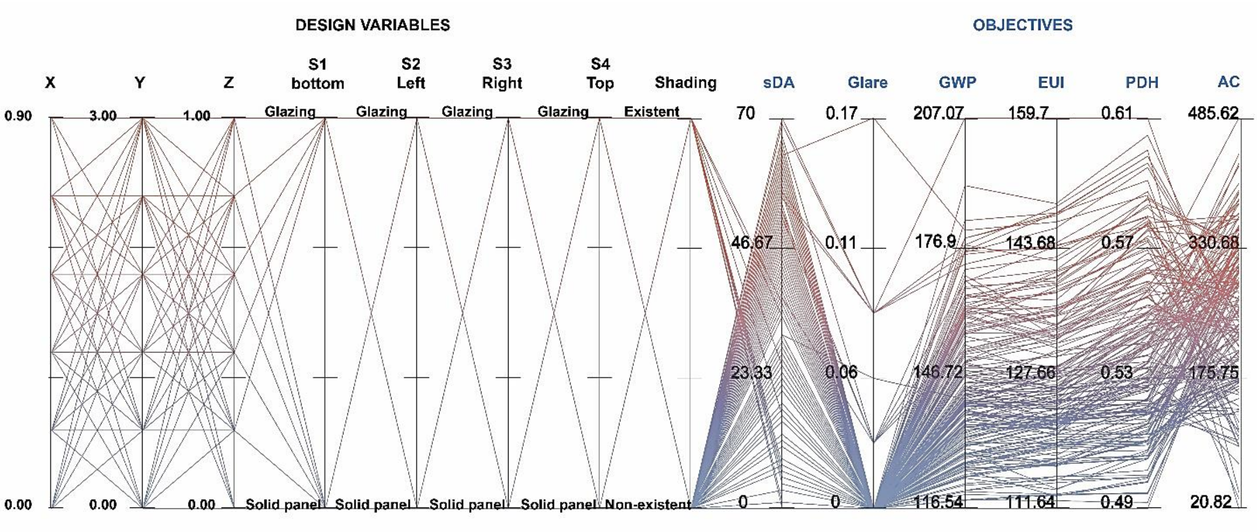


Figure 7.3-10

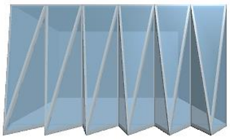
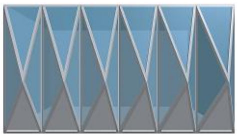
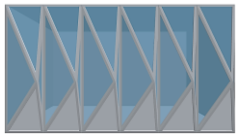
The full spectrum of the optimization results for the north facing façade. The range and distribution of the cases for each objective are displayed.

Daylighting performance

Due to the limited amount of sunlight available to north orientation, only 38 cases from the 196 cases had acceptable daylighting performance (sDA≥ 50%). Moreover, none of the cases reached the preferred threshold of 75% as the maximum sDA was found to be at 70%. Cases with acceptable daylighting performance had a tendency to have larger glazing areas. As a result, the acceptable design had a larger extrusion and all glazing facades with mostly three or two glazing surfaces. table (7.3-15)

Table 7.3-15

North façade designs, variables and daylighting performances for cases with the highest daylighting performance

Cases with the highest daylighting performance for the north orientation			
Façade Design			
Design Variables			
Displacement in X	0.15 m	0.45 m	0.75 m
Displacement in Y	1.00 m	0.60 m	0.20 m
Displacement in Z	0.00 m	1.50 m	1.00 m
Surface 1 (upper-surface)	Double-glazing	Double-glazing	Double-glazing
Surface 2 (right-surface)	Double-glazing	Double-glazing	Double-glazing
Surface 3 (lower-surface)	Fiber-cement panel	Fiber-cement panel	Fiber-cement panel
Surface 4 (left-surface)	Double-glazing	Double-glazing	Fiber-cement panel
Shading	No shading	No shading	No shading
sDA (%)	**70 %**	**66.7 %**	**65.5 %**

Visual comfort

As expected in north facades, the glare occurrence is almost non-existent. As there is no direct sunlight, annual daylight glare probability had a value of 0% in almost all cases.

Energy performance

In order to ensure the minimum heat transfer, north façade designs with low energy consumption had less surface area and overall less glazing area. The façade design with the least EUI (116 kWh/m2/year) had a very minimal glazing area that is almost non-existent. The heating load was much higher than that in south and east orientation due to the lack of direct sun and reached a maximum of 79 kWh/m2/year.

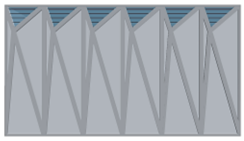
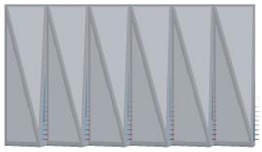
Thermal comfort

Similar to south and east facades, thermal comfort didn't reach satisfactory results. Cases with the least energy consumption were also found to have the least percentage of people dissatisfied. The minimum PDH achieved was 49% and the average annual PDH is between 15-23%. Table (7.3-16) shows the designs with least energy use and PDH.

Table 7.3-16

North façade designs, variables and annual glare probability for cases with the highest visual comfort performance

Cases with the highest energy and thermal comfort performance for the north orientation

Façade Design			
Design Variables			
Displacement in X	0.15 m	0.15 m	0.90 m
Displacement in Y	0.00 m	0.00 m	0.20 m
Displacement in Z	0.50 m	2.50 m	0.00 m
Surface 1 (upper-surface)	Fiber-cement panel	Double-glazing	Fiber-cement panel
Surface 2 (right-surface)	Fiber-cement panel	Fiber-cement panel	Double-glazing
Surface 3 (lower-surface)	Fiber-cement panel	Fiber-cement panel	Fiber-cement panel
Surface 4 (left-surface)	Double-glazing	Fiber-cement panel	Fiber-cement panel
Shading	Horizontal blinds	No shading	Horizontal blinds
Energy use intensity	**116.5 kWh/m2/year**	**118.6 kWh/m2/year**	**125.5 kWh/m2/year**
Average annual PPD	**15%**	**15%**	**15%**

Energy generation

Energy generation was understandably much less than both south and east orientation. The maximum energy generation reached 485.6.5 kWh, which can cover just 12% of the energy use of the same case.

Optimal designs for north facing façade

Overall, 38 cases were found to have an acceptable performance. The overall performance however was found to be the least compared to other two orientations. The design variables and performance results of the five cases with the highest overall performance is shown in table (7.3-17). In most cases, top and side glazing units were essential to provide enough daylight without much sacrifice on other aspects.

Conclusion

The aim of this case study was to evaluate and test the developed framework and design decision support tool in a real-life complex design problem. In this case study, the south, east/west and north façade were optimized. The south and east façades were found to have an overall better performance compared with the north facade. In south orientation, several designs achieved high performance in most aspect. The highest performing case had a spatial daylight autonomy of 70% with a good visual comfort with AGP of 25% and a low end use energy consumption of just 119 kWh/m2/year of which around 8% can be obtained from the BIPV. East facing façade also performed well and even outperformed the south façade in visual comfort. The case with overall heights performance had a sDA of 68%, AGP of 33% and energy consumption of 112 kWh/m2/year of which 15.5% can be generated with the use of BIPV. North oriented facades had lower daylighting performance but better visual comfort. Energy use was also relatively higher and had a lower energy generation due to the absence of direct sunlight. The best design achieved 63% sDA without any glare occurrence and energy consumption of 124kWh/m2/year of which only 2.5% can be substituted by renewable energy generation. In all orientations, the total area of the façade and the glazing units affected the embodied environmental impact. Two-dimensional facades with minimum glazing units were found to have the lowest global warming potential (GWP). In all orientations, several design alternatives with acceptable and high performance were obtained. The designer can, therefore, choose a suitable design for its aesthetics or performance in a specific aspect.

The results show how focusing on a single design objective can most likely results in an overall low-performative design. The use of the integrative performance assessment approach leads to a more variety of designs with an overall high-performance. The different tools developed within the presented framework did not only help in choosing best performing designs but also to have a deeper look for each aspect. Therefore, enables the designers to understand which design variables have the highest impact on the performance of the façade. For this particular case, the three orientation was found to have several high-performance cases. It is understandable that a trade-off process has to take place to arrive at the final decision as there is no design that achieves the highest performance in all aspects. In this case study, a pre-defined threshold was used to filter out the cases with unacceptable performances. A straight-forward scoring method was then used to compare the accepted cases and choose the ones with the highest performances. No biased weights or priorities were given to an aspect over another. However, in real life situation, the user might decide to prioritize specific aspects to have higher performance in certain areas.

Table 7.3-17

Facade designs with the highest overall performance for the north orientation, and their corresponding design variables and performance. Values for the bar- and radar-charts are normalized.

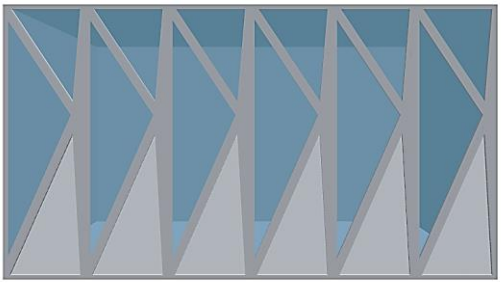
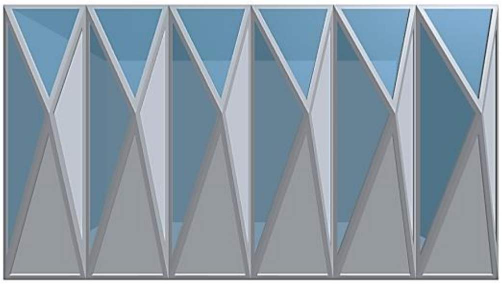
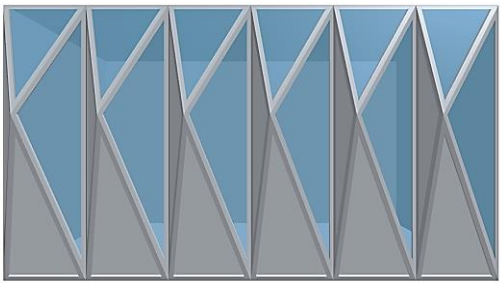
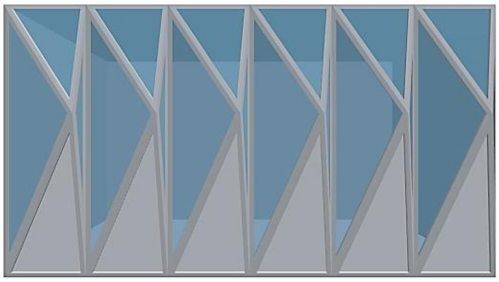
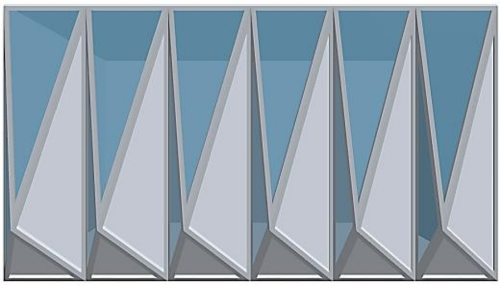
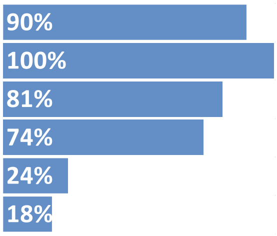
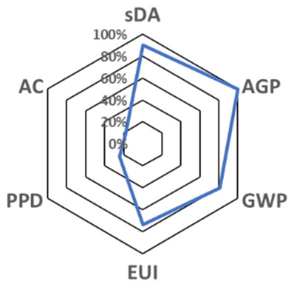
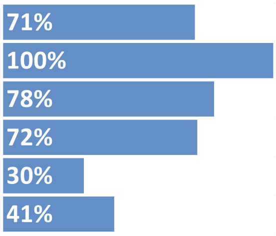
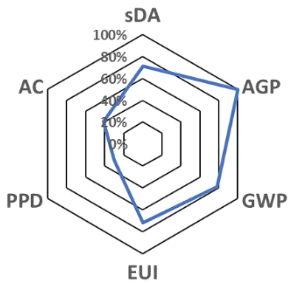
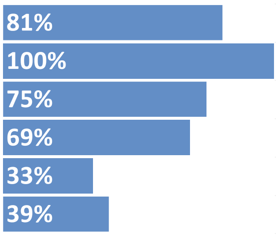
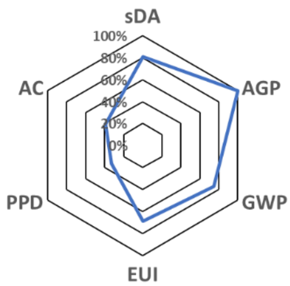
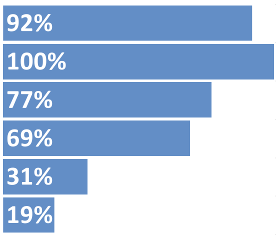
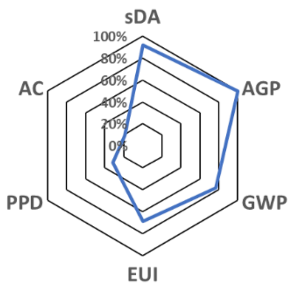
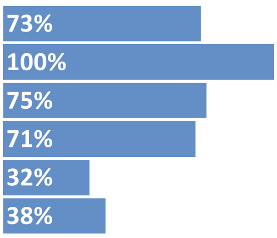
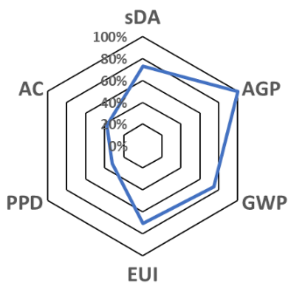
3D Visualization	Design variables	
	Displacement in X	0.75 m
	Displacement in Y	0.00 m
	Displacement in Z	2.00 m
	Upper surface	Double-glazing
	Right Surface	Double-glazing
	Bottom surface	Fiber-cement panel
	Left surface	Double-glazing
	Shading	No shading
	Displacement in X	0.50 m
	Displacement in Y	0.40 m
	Displacement in Z	2.00 m
	Upper surface	Double-glazing
	Right Surface	Fiber-cement panel
	Bottom surface	Fiber-cement panel
	Left surface	Double-glazing
	Shading	No shading
	Displacement in X	0.15 m
	Displacement in Y	0.00 m
	Displacement in Z	2.00 m
	Upper surface	Double-glazing
	Right Surface	Double-glazing
	Bottom surface	Fiber-cement panel
	Left surface	Fiber-cement panel
	Shading	No shading
	Displacement in X	0.90 m
	Displacement in Y	0.20 m
	Displacement in Z	2.00 m
	Upper surface	Double-glazing
	Right Surface	Double-glazing
	Bottom surface	Fiber-cement panel
	Left surface	Double-glazing
	Shading	No shading
	Displacement in X	0.15 m
	Displacement in Y	0.40 m
	Displacement in Z	0.50 m
	Upper surface	Double-glazing
	Right Surface	Fiber-cement panel
	Bottom surface	Fiber-cement panel
	Left surface	Double-glazing
	Shading	No shading

Table 7.3-17 (continued)

Objectives performances	**Bar-chart**	**Radar-chart**
	(Normalized values, higher values indicate better performance)	
sDA 63% [%] AGP 0% [%] GWP 133.55 [kg CO2-e/m2] EUI 123.99 [kWh/m2/year] PPD 52% [%] AC 102.34 [kWh]		
sDA 50% [%] AGP 0% [%] GWP 136.73 [kg CO2-e/m2] EUI 125.01 [kWh/m2/year] PPD 53% [%] AC 209.21 [kWh]		
sDA 57% [%] AGP 0% [%] GWP 139.37 [kg CO2-e/m2] EUI 126.71 [kWh/m2/year] PPD 53% [%] AC 201.50 [kWh]		
sDA 64% [%] AGP 0% [%] GWP 137.18 [kg CO2-e/m2] EUI 126.45 [kWh/m2/year] PPD 53% [%] AC 107.59 [kWh]		
sDA 51% [%] AGP 0% [%] GWP 139.21 [kg CO2-e/m2] EUI 125.55 [kWh/m2/year] PPD 53% [%] AC 199.07 [kWh]		

7.4 Conclusion

In this chapter, the developed framework was further evaluated and enhanced, using feedback from different focus groups and, from a comprehensive design case study. During the focus groups, many ideas and suggestions were discussed, most of which were later included in the framework. The case study focused on evaluating the framework by testing its ability to help the user to arrive at high-performance designs with a real-life complex system. The case study demonstrated the ability of the proposed framework at achieving the aforementioned goal while producing valuable information about the design problem. The framework can be used to simply arrive at the most achieving designs, but it is also possible to present more design information by visualizing the simulation results and using the exploring and comparing tools within the framework.

Chapter 8: Conclusions and Outlook

8.1 Summary

The goal of this doctoral research was to develop and present a novel design decision support framework and tool to aid designers in arriving at high-performance building facades. The research focused on the environmental performance of the façade and followed an integrative approach to assess building facades for its daylighting performance, visual comfort, energy performance, thermal comfort, embodied environmental impacts, as well as energy generation.

Following a design research methodology, an intensive literature review was conducted at the beginning of this dissertation (Chapter 2 and Chapter 3), which aimed to better define the façade performance within the scope and limits of this research as well as discussing the state-of-the-art methods and tools for the integrative assessment and optimization of building facades. The results and information from the literature review were then used in developing the Integrative Performance Optimization (IPO) framework in Chapter 4. The framework utilizes a parametric modeling tool to create a vast number of design alternatives. The design alternatives are then analyzed and optimized for their integrative environmental performance using simulation and optimization tools. The framework was tested using case studies in Chapter 5 to define the limitations and the required enhancements. The results and findings of the case studies were later used to enhance the framework and the development of the design decision support tool in Chapter 6. Finally, in Chapter 7 the developed framework was evaluated using a number of focus groups and a holistic case study. The research work has resulted in a number of conclusions, which are discussed in the following section.

8.2 Conclusions

The research efforts presented in this thesis have resulted in the following main conclusions:

The modern and future facades are expected to have more functions and achieve higher performance. Due to the use and progress of computational tools more options and façade design could be obtained. However, that also complicates the problem of choosing the right values for the different façade design variables to achieve better performance. The use of state-of-the-art computational design, simulation, and optimization tools is essential.

A vast number of modeling tools are now available for designers with different degrees of complexity and sophistication. Most of the design decision support and simulation tools are very limited in their modeling capabilities to building forms with rectilinear, and orthogonal shapes, with regular horizontal rows of windows. The use of parametric modeling, on the other hand, allows for a higher degree of complexity and enable the designer to investigate more complex façade systems such as that shown in Chapter 7. The research, therefore, highlights the advantages and promotes the integration of parametric design tool in building performance simulation and optimization frameworks.

The importance of using an integrative environmental simulation approach was discussed and highlighted in several areas of this research. In the three case studies analyzed in this research, it was constantly noted how depending on a single performance aspect can be deceiving and can lead to arriving at designs with lower performance in other design aspects. The certain number of design aspects can differ from a case to another, depending on the project and the relative importance of the design aspects. Nevertheless, a minimum number of design aspects that ensures the comfort of the building users and having a low environmental impact of the design should always be considered. In this research, an integrative performance assessment was proposed which included the numerical assessment of daylighting performance, visual comfort, energy performance, thermal comfort, embodied environmental impacts, as well as energy generation.

Multi-objective optimization was used extensively in this research. The use of optimization tools was found useful, especially for design exploration and with a vast number of alternatives. While it is not always guaranteed to arrive at a best performing or an optimum design, the optimization results can be used in narrowing down the design options and the variables ranges. In the three case studies, that were analyzed in this research, the coupling of multi-objective optimization and integrative simulation resulted in high performance designs. Moreover, the case studies result and conclusions, which were discussed in the corresponding chapters, showed that the use of multi-objective optimizations can help in understanding the relations between the design variables and objectives and produce general interpretations and guidelines.

As discussed in the case studies, multi-objective optimizations result in a large amount of data and simulation results. Data analysis and visualization tools are essential to effectively extract useful information. Many design decision support tools were developed to help the designers and architects in making informed decisions at the early design stages. Nevertheless, most of these tools have critical limitations in the modeling methods, results visualizations and types of performance assessments it can undertake.

A prototype of a design decision support tool was developed to serve as an Integrative Performance Assessment Dashboard (IPAD). The IPAD tool can help the designers to efficiently analyze the results of building performance multi-objective optimizations. The evaluation of the tool and feedback from the focus groups and case studies highlight the potential as well as the limitations of the tool.

8.3 Contribution to knowledge

The main contribution of this research can be seen in the development and testing of a prototype for a design decision-support (DDS) tool. The developed tool overcomes a few of the main limitations in current DDS tools by:

- linking the framework with parametric modeling tools, therefore, provide more freedom to the designer.
- using a holistic approach to provide an integrative assessment for the different performance aspects
- providing a user-friendly visualization interface that can be more effective in the decision-making process.

The new approach paves the way for other improvements and enhancements and highlights the importance of design research methodologies in the architecture and building environment domain. While computational methods and tools are being developed at exceptional speeds in nearly every sector, architecture, and construction domains are catching up on a rather slower pace.

The importance of simulation and optimization results visualization as an essential tool in interpreting the results and making design decisions was also highlighted. Results analysis and visualization for building performance simulation is still relatively a new area that may need further and continuous development. The focus groups helped in clarifying this point by clarifying the user priorities and needs.

The research also highlights the use of the iterative process within the design research methodology. Looking at the result of this research, and any design product at that matter, as a product of continuous development that can always benefit from another cycle of user feedback and improvements.

8.4 Limitations and outlook

Several limitations were defined at the beginning of this research. Starting with the domain of study, while this research focused exclusively on buildings facades as a critical building element, the same methodology can be extended and applied to other building elements or building types. The same is also true with the focus of this research on the environmental impacts of the building, which can be extended to other areas such as structure performance and cost estimates.

For this particular research and the developed tool, an interesting and important outlook could be in linking the tool with Building Information Modeling (BIM), which provides numerous options of developments and enhancement by using the data stored in the BIM models. That can also facilitate the addition of other functions to the framework that was restricted due to the lack of complete data sets such as full life cycle assessments and life cycle cost studies. Another promising opportunity that also addresses the restriction of incomplete data, lies in modeling and dealing with uncertainties. Uncertainty-based design optimization is a promising research area that can offer a lot in the development of design decision tools. The use of other rapidly developing optimization methods such as machine learning and deep learning techniques might as well be a topic of future research.

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Glossary

Annual glare probability: a visual comfort indicator and simplified method in which the daylight glare probability is measured for different times and dates throughout the year (such as first and mid-days of each month or the equinoxes and solstices) to represent an annual glare performance.

Annual sunlight exposure (ASE): represents the percentage of the floor area that receives more than 1000 lux for at least 250 occupied hours per year.

Base case model: a reference model or design that is used in evaluating the performance of other designs.

Building integrated photovoltaics (BIPV): photovoltaic materials integrated into whole building design and construction

Building performance optimization: the use of optimization tools and algorithms to enhance the performance of the building. Optimizations can be carried out for a single objective or for more than one objective (Multi-objective optimization).

Building simulation: a replica or reproduction of the physical behavior of buildings and building (sub)systems, based on physical modeling of the system, development of mathematical equations that describe the behavior, solution of these mathematical equations, and presentation and visualization of the resulting output. The most relevant behavioral aspects studied in building simulation are heat transfer, (day)lighting, acoustics, and air flow.

Continuous daylight autonomy (DAcon): a dynamic daylighting performance indicator and is a modified version of the daylight autonomy metric. Continuous daylight autonomy gives a partial count to times when the daylight illuminance at a given point lies below the task/ambient lighting threshold. This method becomes useful for showing the potential energy savings if the electric lights have dimming or multi-level switching capabilities.

Data visualization: presenting data and summary information using graphics, animation, and 3-dimensional displays. Tools for visually displaying information and relationships often using dynamic and interactive graphics.

Daylight autonomy (DA): a dynamic daylighting performance indicator, which is defined as is the percentage of the occupied hours of the year when a minimum illuminance threshold is met by daylight alone.

Daylight factor (DF): a daylighting performance indicator and is defined as the ratio of the internal illuminance at a work-plane point in a building to the un-shaded, external horizontal illuminance under an overcast sky.

Daylight glare index (DGI): a visual comfort indicator that was the first metric to consider large glare sources such as sky viewed through the window.

Daylight glare probability (DGP): a visual comfort indicator that represents the probability that a person is disturbed by glare and is derived from a subjective user evaluation. Annual DGP calculates the DGP for each occupied hour for the entire year.

Daylighting performance: the availability of sufficient daylight for the building users that enables them to achieve the function, which the space was built for without the need for additional artificial lighting.

Design decision support tool (framework): in the context of this thesis, a computer-based model that consists of a software or a group of software packages to provide design decision support.

Design decision support: the use of a model, tool or technique, usually computer-based, to help identify and solve problems, make decisions and in general assist and support decision making.

Dynamic daylight performance metrics (DDPM) or **climate-based daylight metrics (CBDM):** a group of daylighting performance indicators, that quantifies the amount of daylight available in a building space, based on annual illuminance or luminance profiles. These values are usually generated from a weather file and are utilized through hours of occupancy.

Energy efficiency: Energy efficiency refers to the use of less energy to provide a satisfactory level of comfort. The energy use intensity in kilowatt-hours per square meter is generally used to compare the levels of energy efficiency between different buildings.

Energy use intensity (EUI): a performance indicator widely used to determine the energy performance of buildings and other facilities and is measured in kilowatt-hours per square meter (kWh/m^2).

Evolutionary algorithm: an iterative process, typically computationally driven, that seeks to improve a condition where each new iteration is an improvement compared to the previous one until an optimized condition is reached. Each iteration is measured according to a fitness function, and only the iterations with the highest performance are reintroduced to subsequent iterations.

Fitness function: a quantifiable process that measures a condition against a set of rules for an ideal or desired condition.

Genetic algorithm: a computational search method that mimics the process of natural selection.

Glare: a phenomenon that involves a difficulty of seeing in the presence of bright light. Because of this, some cars include mirrors with automatic anti-glare functions. Glare is caused by a significant ratio of luminance between the task (that which is being looked at) and the glare source.

Isovist: a view indicator which is defined as the volume of space visible from a given point in space, together with a specification of the location of that point.

Life cycle analysis: is a technique to assess environmental impacts associated with all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling.

Maximum to minimum illuminance ratios: a visual comfort indicator that helps in detecting glare and unbalanced illuminance on the work plane. A work plane calculation must be performed to find the point illuminance at the desired time of year, or the averages based on an annual calculation. Computer simulation is then carried out to find the work plane extremes so the maximum to minimum illuminance ratio can be calculated.

Parametric modeling: a form of computational modeling in which the object is defined using mathematical equations and can be manipulated by changing the equation parameters.

Pareto-optimal: an outcome that cannot be further improved without making particular aspects of it worse. For a given problem there may be multiple Pareto-optimal solutions, each one a little bit worse in specific aspects and a little bit better in others than the other Pareto-optimal solutions.

Passive design: Passive design concept uses natural resources instead of electricity or fuel to provide the best indoor comfort for building users. These strategies include daylighting, natural ventilation, and solar energy.

Percentage of discomfort hours (PDH): the percentage of the occupied hours of the year at which the indoor climate conditions are not satisfying for 10% or more of the space users.

Performance aspect: field of action for which the building is to perform a required function (e.g. energy efficiency, thermal comfort, etc.).

Performance-based design (Performative design): The use of building performance and metrics as guiding principles in architectural design.

Performance indicator: a value or set of values that quantify the performance of a system for a given performance aspect if subject to a given experiment.

Performance metrics: a performance metric is a measure of the overall performance of a building; it can be a measurable quantity (e.g. minimum lux on the desktop) or a qualitative measure (number of hours per year the minimum lux is provided by daylight, without exceeding some defined glare criterion) or a combination of both.

Predicted mean vote (PMV): a thermal comfort indicator that was adopted as an ISO standard. It predicts the average vote of a large group of people on a seven-point thermal sensation scale.

Predicted percentage of dissatisfied (PPD): a thermal comfort indicator that predicts the percentage of thermally dissatisfied people who feel too cool or too warm, and is calculated from the predicted mean vote (PMV)

Sensitivity analysis: the study of how sensitive an outcome is to changes in parameters. This is typically analyzed by slightly varying the parameters to an equation and measuring the difference in the outcome. Often used in energy analysis to determine what component or parameter is having the most effect on energy consumption.

Single point in time (SPT): a daylighting performance indicator, in which illuminance calculation is measured at a specific surface for a single time of the year. The time can be selected to represent an average daylight condition, such as sunny equinox at noon or an extreme scenario, such as cloudy winter solstice.

Spatial daylight autonomy (sDA) a recent method and dynamic daylighting performance indicator. **$sDA_{300Lux/50\%}$** is used to evaluate the presence of sufficient daylight by calculating the percentage of the floor area that receives 300 lux or more for at least 50% of the annual occupied hours, while

Thermal comfort: thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation."[1]. It depends on the air temperature, humidity, radiant temperature, air velocity, metabolic rates, and clothing levels.

Useful daylight illuminance (UDI): a dynamic daylighting performance indicator, that calculates the total number of occupied hours that “useful” daylight enters a space at a select point. Useful daylight is defined as providing ambient light at the work plane at illuminance levels between 100 lx to 2,000 lx.

U-value: the term U-Value, or thermal transmittance, is the rate of heat transferred through a building structure, divided by the difference in temperature across that structure. U-values are measured in Watts per square meter per degree Kelvin (W/m^2K). The lower the U-value of a building component, the better it insulates.

Visual comfort: a subjective perception of the suitability of lighting taking into account uniform illumination, optimal light levels, glare, contrast, correct colors, and the absence of stroboscopic effect or intermittent light.

Visual programming language (VPL): a programming language that uses graphic elements to create a program. Examples of these used in conjunction with architecture design software include Grasshopper and Dynamo.

[1] ASHRAE (2005). ASHRAE Handbook Fundamentals. SI Edition, p 8.1-8.29.

Appendices

Publications

The following publication were published in the course of this PhD research:

- Gadelhak, M., & Lang, W. (2016). Optimization of Office Building Façade to Enhance Daylighting, Thermal Comfort and Energy Use Intensity. In N. Hamza & C. Underwood (Eds.), Proceedings of the 3rd IBPSA-England Conference BSO 2016, Newcastle, 12th-14th September 2016.

- Gadelhak, M., Lang, W., & Petzold, F. (2017). A Visualization Dashboard and Decision Support Tool for Building Integrated Performance Optimization. In A. Fioravanti, S. Cursi, S. Elahmar, S. Gargaro, G. Loffreda, G. Novembri, & A. Trento (Eds.), *ShoCK! - Sharing Computational Knowledge! - Proceedings of the 35th eCAADe Conference, 20-22 September 2017* (Vol. 1, pp. 719–728). Sapienza University of Rome, Rome, Italy.

- Gadelhak, M., & Wageh, M. A. (2017). Optimization of Facade Design for Daylighting and Viewto-Outside: A case study in Lecco, Lombardy, Italy. In A. Fioravanti, S. Cursi, S. Elahmar, S. Gargaro, G. Loffreda, G. Novembri, & A. Trento (Eds.), ShoCK! - Sharing Computational Knowledge! - Proceedings of the 35th eCAADe Conference, 20-22 September 2017 (Vol. 1, pp. 229-236). Sapienza University of Rome, Rome, Italy.

OPTIMIZATION OF OFFICE BUILDING FAÇADE TO ENHANCE DAYLIGHTING, THERMAL COMFORT AND ENERGY USE INTENSITY

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ABSTRACT

The aim of this paper is to examine a framework in which an office building façade was optimized for the integrated performance of total energy consumption, daylight quality and thermal comfort. A south facing façade of an office space was modelled parametrically for two case studies in Cairo and Munich. The effect of changing the window dimensions, glazing system, insulation thickness, as well as different shading and daylighting systems was analysed using Radiance and EnergyPlus simulation tools. A multi-objective optimization was performed to reach an optimal range of solutions. The results from each case study and the relations between the design variables and objectives for each case were studied. Moreover, the practicality of using a simulation-based multi-objective optimization in generating high-performance design alternatives was examined. The results show that the use of multi-objective optimization for complicated design problems can aid in reaching performative solution and clarify the relations between the design variables and objectives.

INTRODUCTION

Building facades have great impact on the whole building performance. It must fulfil a number of vital functions while maintaining the energy consumption of the building as low as possible. A good façade design should help in saving energy while protecting the building occupants from external climate conditions and provide them with comfort. Due to the numerous variables that affect the overall building performance and the multi-objective characteristic of the building performance, architects and designers usually use a trade-off approach to design building facades with better performance.

Passive design strategies are typically used to enhance the performance of facades. Some of the most used strategies include reducing the glazing area, using high performance glazing system, and the use of daylight and shading systems. Reducing the Window-to-Wall Ratio (WWR) is one of the main principles of low-energy buildings design. Most guidelines and standards aim at limiting the glazing area to WWR≤30% but mainly focuses on the energy savings from the HVAC systems without considering the trade-off between lighting loads and HVAC (Lee et al., 2009). Minimizing glazing area can have a negative impact on daylighting availability and distribution, hence increasing the energy load and resulting in poorly daylit working spaces. Moreover, the presence of shading devices can change the optimum WWR (Mangkuto et al. 2016).

Shading and daylighting systems play a significant role specially in side-lit office spaces. The effect of using shading devices with different WWRs on both daylighting and energy use was investigated by several previous studies. A recent review by Krimitat et al. (2016) shows a noticeable increase in number of research papers that examine the performance of shading devices. In a recent research paper by Reinhart et al. (2013) it was found that larger but well shaded glazing areas can provide an overall better performance as it provides better daylighting with insignificant effects on energy use. Optimum WWR also depends on glazing type. Using high-performance glazing systems of several panels and low-e coatings can aid in maintaining reasonable window sizes and good daylighting without compromising energy savings. Hee et al. (2015) reviewed research work on a large number of glazing systems. It concluded that achieving the balance between daylighting and energy remains a crucial and complicated measure that depends on several factors of which the climate background was found to be the most important.

Another vital strategy is the reduction of heat transfer from the building envelope by using suitable wall insulation. According to a recent review by Papadopoulos (2005) thermal insulation remains the most cost effective approach in reducing energy consumption in both new constructions and retrofitted buildings. The thickness of insulation needed and overall wall U-value differs according to geographic locations and climate. Local codes and guidelines usually define the minimum insulation needed to insure a suitable performance of the building envelope. Standards and guidelines for passive strategies are most helpful when dealing with limited objectives and variables. However, when dealing with several variables and objectives it becomes more complicated specially when some of these objectives are conflicting. In such cases, the use of simulation-based optimization methods was found to be an effective approach. Multi-objective optimizations in particular is found to be promising due to the complex and multi-objective nature of design problems. In contrary to single objective optimization, multi-objective optimization doesn't result in a single optimum solution but rather a whole set of possible solutions of equivalent quality (Abraham et. al., 2005). Therefore, decisions could be taken by considering the trade-offs between conflicting objects. Some of the early work on using GA optimization in buildings design was presented by Caldas & Nordford (2002). Several recent research works used this technique in architecture, engineering and construction (Wright, et al. 2013; Asl. et al. 2014; Ashour, & Kolarevic, 2015). Recent publications investigated the trends of the use of optimization tools in research related to building performance. Evins (2013), presented a review for most of the significant work that utilized optimization tools in sustainable building design. The review showed a major increase in the use of optimization tools. It also highlighted the opportunity for future development as nearly half of the research work focused on single objective problems that can be extended by adding more objectives. In another review by Attia et al. (2013), recent publications were classified according to the objectives and design variables. In both reviews some limitations were drawn including the computation time, ease of use, and uncertainty. This paper aims to investigate the practicality of using multi-objective optimization in providing high-performance façade designs. That is made by examining a framework in which building façade is optimized for the integrated performance of total energy consumption, daylight quality and thermal comfort. The optimization variables are the glazing area, glazing system, insulation thickness, and a variety of shading and daylighting systems with different variables.

METHODOLOGY

Parametric model

A parametric model of a south facing single office space was created using Grasshopper plugin for the Rhino 3D CAD software. The office room was assumed to have the dimensions of 4.00m x 6.50m x 3.00m for the width, depth and height respectively.

Daylighting performance, energy use and thermal comfort were analysed. Simulations were performed for two cities: Cairo, Egypt (30°3′N 31°14′E) with hot arid climate and Munich, Germany (48°8'N 11°34'E) that has a temperate humid climate according to Köppen-Geiger climate classification (Kottek et al. 2006). Different settings for the glazing area, glazing system, shading, daylighting system and insulation system were modelled parametrically. The glazing area is divided into upper and lower parts, where the upper part acted as a clearstory window. Both window parts were introduced to the shading devices separately. Seven WWRs were studied together with four glazing systems, four shading systems for each of the windows, and four light-shelf settings. Additionally, the building insulation was increased gradually with 2.5 cm steps until it reaches a total of 25 cm. Overall nearly 20,000 design alternatives could be generated. The details of the parameters are described in the following table (Figure 1, Table 1).

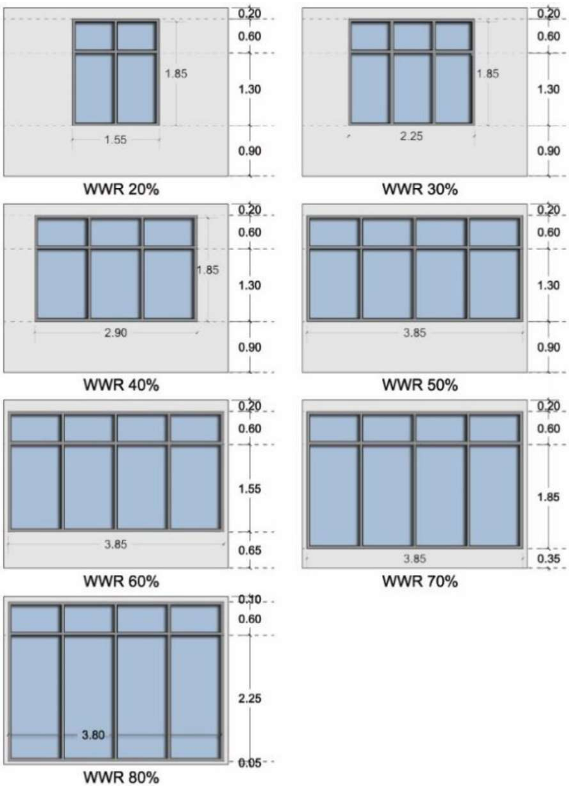

Figure 1 Different WWRs investigated

Table 1 Design variables

Design Variable	Type	Possible Values	No. of options
WWR	Continues	From 10% to 80% (10% step)	7
Insulation Thickness	Continues	From 0.0 to 25.0 cm (2.5 cm step)	11
Glazing system	Discrete	- Single glazing - Double Glazing - Double Glazing with low-e coating - Triple glazing	4
Shading systems (for each window)	Discrete	- No shading - Horizontal shades - Vertical shades - Solar screen	16 (4x4)
Daylight systems (light-shelves)	Discrete	- No light-shelf - External - Internal - External and internal	4
Total number of design alternatives			19,712

Table 2 Radiance simulation parameters

	Ambient bounces	Ambient divisions	Ambient sampling	Ambient accuracy	Ambient resolution
sDA /ASE	6 / 0	1000	20	0.1	300

Base case

The research approach in this paper was based on a cross comparison of simulation results. A base case was defined in order to make it easier to evaluate and judge these results. It was assumed to have an un-insulated external wall, WWR of 20%, with double glazing, and without any shadings or light-shelves.

Daylighting simulation methodology

The effect of changing the variables on daylighting performance was measured using DIVA-for-Rhino (V 3.0), a Rhino 3D plugin that is used to interface Radiance and Daysim for annual simulation and illuminance computation (Jakubiec, & Reinhart, 2011). Daylight performance was evaluated using the IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) criteria which corresponds to the latest progress in daylighting simulation metrics introduced in the Illuminating Engineering Society standard IES LM- 83-12 (IESNA, 2012). $sDA_{300Lux/50\%}$ was used to evaluate the presence of sufficient daylight by calculating the percentage of the floor area that receives 300 lux or more for at least 50% of the annual occupied hours. Solutions that achieve sDA ≥ 50% are accepted while sDA≥75% is preferred. The annual sunlight exposure was used to describe the percentage of floor area that receives too much direct sunlight and is used as an indication for visual discomfort (glare) and excessive heat gain. ASE represents the percentage of the floor area that receives more than 1000 lux for at least 250 occupied hours per year. Occupancy hours were assumed to be daily from 8AM to 6PM with hour-saving time. The calculations were made for a reference plane of 60 measuring points in a grid of 0.6m* 0.6m, at a working-plane of 0.85 m height. Simulation parameters are shown in Table 2, and the optical properties of the materials used are presented in Table 3.

Energy simulation methodology

For energy simulations, the Ladybug+Honeybee plugin (Roudsari, M. S. & Pak, M., 2013) was used to interface the EnergyPlus simulation program (US-DOE 2015). The energy use for each design alternative was calculated hourly throughout the whole year for cooling, heating, lighting and equipment loads. The annual energy use per floor area (EUI) was used to compare the efficiency of each design. All surfaces of the tested office space were assumed adiabatic, except the external wall with the glazing. The detailed thermal properties are described in Table 3. Equipment loads were assumed to be 8 W/m^2 and the lighting power density 11.8 W/m^2. Lighting load schedules were obtained from the daylighting simulation and the occupancy and equipment load schedules were identical to those used in daylighting simulation. During occupied hours it is assumed that 4 people are present. The space was considered to be fully air conditioned and the HVAC cooling and heating set points were set at 24°C and 20°C respectively.

Thermal comfort

Thermal comfort was evaluated using the Predicted Mean Value model (PMV). The PMV comfort calculator from the Ladybug+Honeybee plugin was used to calculate the Percentage of People Dissatisfied (PPD) for each hour. Operative temperature, mean radiant temperature and relative humidity were obtained from the energy simulation, while both metabolic rate and clothing level were set to 1 *mat* and 1 *clo* respectively. Since the HVAC set point, metabolic rate and clothing level are set to constant values, changes in thermal comfort is due to change in the mean radiant heat derived by the change in the façade construction, glazing type and area. Percentage of Discomfort Hours (PDH) which is the percentage of hours that had PPD more than 10% was aimed to be minimized.

Table 3 optical and thermal properties for building materials

Building element	Properties	
Glazing	Single glazing	τ_{vis}= 0.88; SHGC= 0.82; U-Value= 5.82 W/m^2K
	Double glazing clear	τ_{vis}= 0.80; SHGC= 0.72; U-Value= 2.71 W/m^2K
	Double glazing low-e coating	τ_{vis}= 0.65; SHGC= 0.28; U-Value= 1.63 W/m^2K
	Triple glazing Krypton filled	τ_{vis}= 0.47; SHGC= 0.23; U-Value= 0.57 W/m^2K
External wall	Medium colored with 35% reflectance;	
	20cm Concrete block + 2cm cement plaster each side (U-value = 3.1 W/m^2K);	
	Thermal insulation thickness (0 to 25 cm); Insulated walls U-Values: 0.91 to 0.114 W/m^2K	
Internal walls	Medium colored with 50% reflectance; adiabatic	
Ceiling	White colored with 80% reflectance; adiabatic	
Floor	Carpet floor with 20% reflectance; adiabatic	
External ground	Dark colored with 20% reflectance	
Furniture	Medium colored with 50% reflectance	
Horizontal shadings	Medium colored with 50% reflectance; vertical shading angle = 45°	
Vertical shadings	Medium colored with 50% reflectance; horizontal shading angle = 45°	
Solar screen	Medium colored with 50% reflectance; perforation ratio: 80%; openings proportion: 2:1 (H:V)	
Light-shelf	High-reflective surface with 90% reflectance	

The multi-objective optimization workflow

The multi-objective optimization was performed using the Grasshopper's plug-in Octopus (Vierlinger, & Hofmann, 2013). It is based on the evolutionary algorithm SPEA-2 developed at ETH Zurich (Zitzler, et al. 2001) and applies evolutionary principles to provide Pareto-optimal solutions. A solution is considered a Pareto-optimal if no other solution exists that "would decrease some criterion without causing a simultaneous increase in at least one other criterion (assuming minimization)" (Coello et al. 2006). In other words, Pareto-optimal solutions are non-dominant solutions that are considered as equal solutions. A trade-off between the objectives is therefore essential to judge them. Annual Sunlight Exposure was used as a Boolean objective, so that only cases that achieved ASE less than 10% were considered in the optimization. The optimization was performed for the previously mentioned variables and three objective functions were used: the sDA, EUI and PDH. For each of the two studied locations, the optimization process continued for 10 generations with a population size of 30. Mutation rate was set as 0.5, mutation probability as 0.1 and crossover as 0.8. The optimization workflow is shown in Figure (2). Results were then exported and analysed using Excel and parallel coordinates graphs created by a web-based application "Pollination" (Pollination, 2015).

RESULTS

Simulation and optimization results for Cairo

The base case was found to have an acceptable daylight autonomy with sDA= 65%, however, the overall daylighting performance was considered unacceptable due to the high penetration of sunlight (ASE = 28%). It had a high energy use of 193 kWh/m^2/yr, and a very poor thermal comfort performance (PDH 70%). The main reason behind such poor results was primarily the lack of proper wall insulation and shading. During the optimization 133 unique designs were analysed. Daylight autonomy ranged from 7% to 100%, the lowest energy use intensity was 133 kWh/m^2/yr while thermal comfort ranged between PDH = 2% and 75%. The effect of the design variables on each optimization objective is discussed in the following sections and presented in Figure (3).

Daylighting

Forty-three cases achieved the daylighting threshold and nearly quarter of the cases had better performance than the base case. Cases with preferred daylighting performance tended to have a 50% to 80% WWR, with single, double glazing or low-e coated double glazing. Shadings and light shelves were present in almost every case with few exceptions where it was not needed for the upper window. Three cases achieved the maximum sDA of 100% which is a considerable enhancement given that these cases also had ASE less than 10% and a slightly higher energy use than the base case.

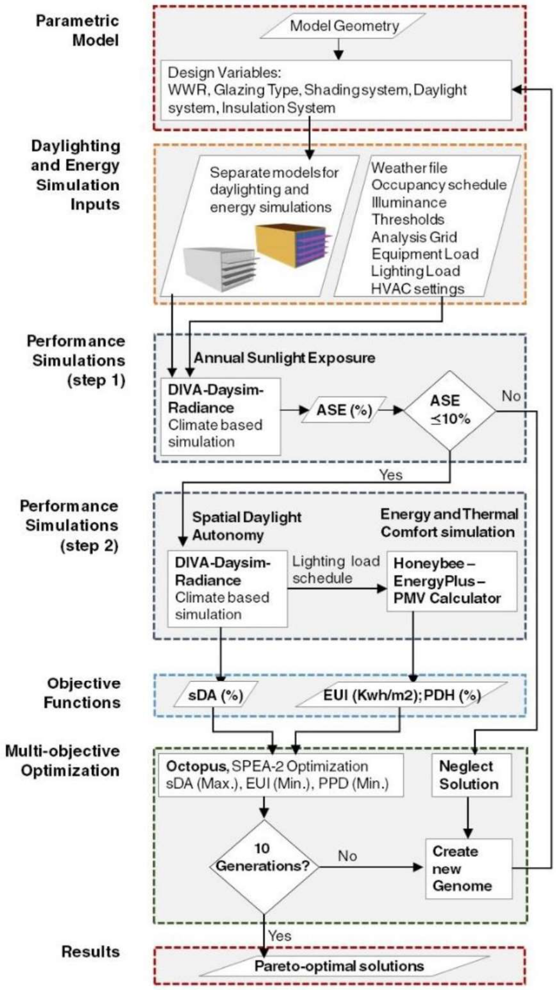

Figure 2 Optimization process diagram

Energy use

Energy savings reached more than 30%. Thermal insulation presented in all cases with an average of 12.5 cm thickness. It played an evident role in reducing the energy consumption and cases with the lowest EUI (133 and 136 kWh/m^2/yr) had maximum insulation thickness (25 cm). Nevertheless, several cases achieved low EUI with lower insulation thicknesses. The combined effect of high performance glazing with shading and light shelves facilitated the increase of the WWR without compromising the energy use, and cases with lowest energy use tended to have larger windows (60-80%). That is mainly because shaded glazing with low U-value helped in maintaining the cooling loads at almost a constant level while large glazing area provided significant savings in lighting loads.

Thermal comfort

Thermal comfort was enhanced steadily throughout the optimization where PDH reached a minimum of 2%. The most effective measure on thermal comfort was the WWR, and most efficient cases had the smallest possible windows (20% WWR), however it didn't achieve sufficient daylighting. The lowest PDH with sufficient daylighting performance was found to be 14% with 30% WWR.

Pareto-optimal

Thirty-six Pareto-optimal solutions were found, from which eleven cases achieved a satisfactory sDA of 50% or more. The majority of the optimal solutions had WWR between 60-80%, double low-e glazing and shadings on both parts of the window. Thermal insulation was also present in all optimal cases with thickness of 12.5 cm or larger. The acceptable optimal solutions are presented in Table (4).

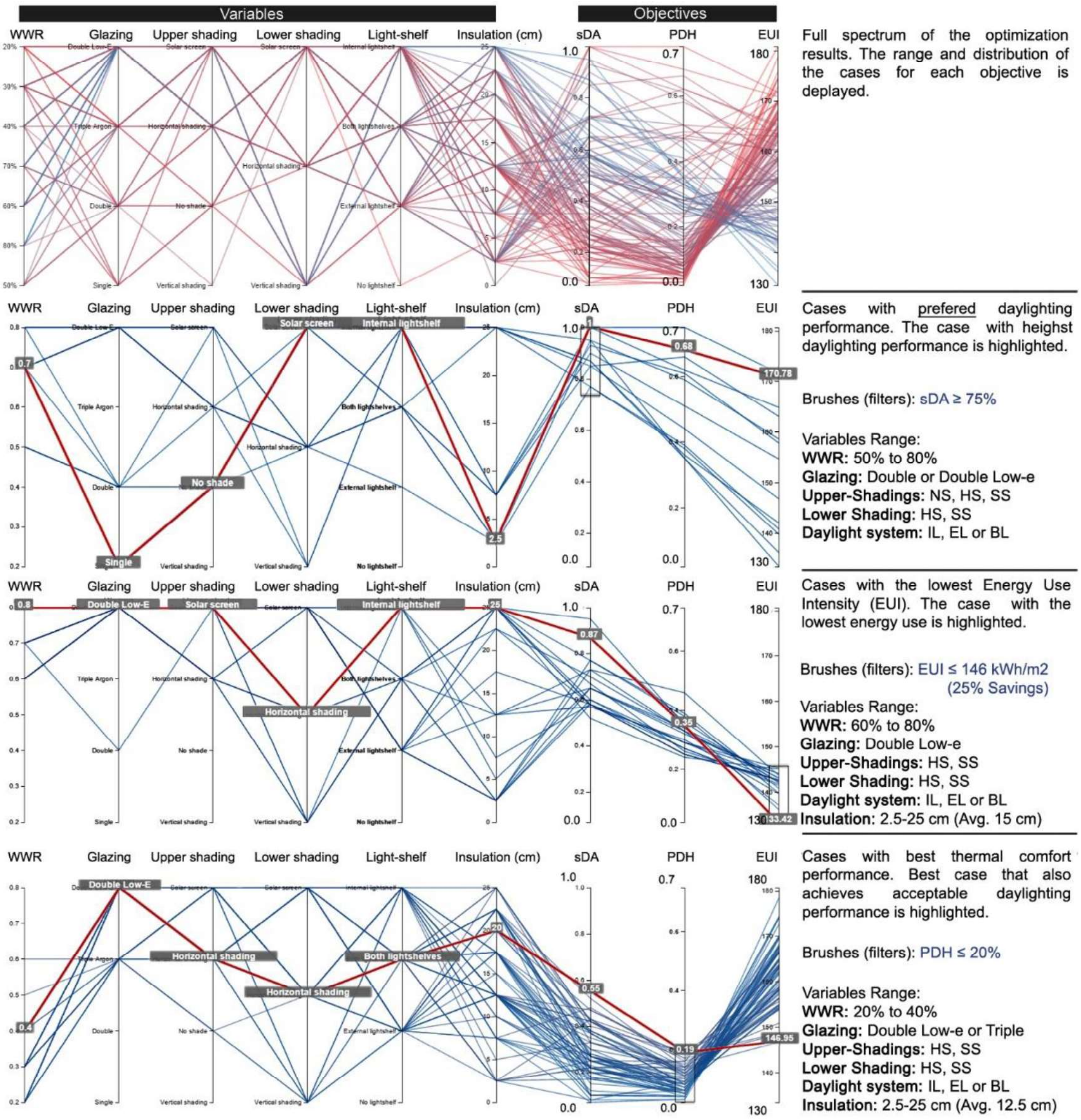

Figure 3 Parallel coordinates plots for the simulated and most performative cases for each objective in Cairo.

Table 4 Design variables and objectives values for Pareto-optimal solutions in Cairo.

WWR	Glazing	Upper-Shading	Lower- Shading	Light-shelf	Insulation (cm)	sDA (%)	PDH (%)	EUI (kWh/m2/yr)
0.70	Single	No shade	Solar screen	Both	2.5	100%	62%	164.88
0.80	Double Low-E	Horizontal	Horizontal	Internal	25	95%	35%	136.18
0.80	Double Low-E	Solar screen	Horizontal	Internal	25	87%	35%	133.42
0.80	Double Low-E	Horizontal	Solar screen	External	12.5	73%	33%	137.14
0.70	Double Low-E	Horizontal	Vertical	Both	22.5	70%	33%	143.17
0.60	Double Low-E	Horizontal	Vertical	Both	25	67%	26%	142.54
0.60	Double Low-E	Solar screen	Horizontal	Internal	12.5	65%	33%	142.39
0.60	Double Low-E	Horizontal	Solar screen	External	25	60%	27%	141.48
0.60	Double Low-E	Solar screen	Solar screen	External	22.5	58%	25%	142.63
0.80	Double Low-E	Solar screen	Solar screen	Both	12.5	57%	30%	139.69
0.40	Double Low-E	Solar screen	Vertical	Internal	12.5	57%	21%	148.11

Simulation and optimization results for Munich

The base case achieved accepted sDA of 55%, however the ASE reached 23%. This resulted in an EUI of 133.85 kWh/m^2/yr and Thermal comfort of PDH= 62%. During the optimization process 145 unique cases were generated. Daylight autonomy ranged from 7% to 85%. The lowest energy use intensity was 91 kWh/m^2/yr. Thermal comfort ranged from 27% to 69%. (Figure 4)

Daylighting

Only one case achieved a preferred performance were the sDA reached 85%. Several design alternatives with most WWR and glazing types achieved acceptable sDA, with the exception of cases with WWR equal to 20% and 40%. For the upper window solar screen, horizontal shading and even unshaded glazing was found to be useful. On the other hand, cases with unshaded lower window, vertical shading or without light-shelves had a high penetration of direct sunlight that resulted in a high ASE and therefore were excluded during the optimization. Light-shelves in particular were found to be effective, as all successful cases had light-shelves.

Energy use

The energy use was reduced drastically throughout the optimization from 133 to only 91 kWh/m^2/yr, with nearly 30% reduction. The effect of wall insulation and high efficient glazing are the main reason behind this reduction. It is worth noting that the cases with the least energy use had also much lower WWR, which affected the daylight performance. Nonetheless, a Pareto-optimal case achieved sufficient daylighting with only 92.3 kWh/m^2/yr. Once more horizontal shading and solar screens were found effective.

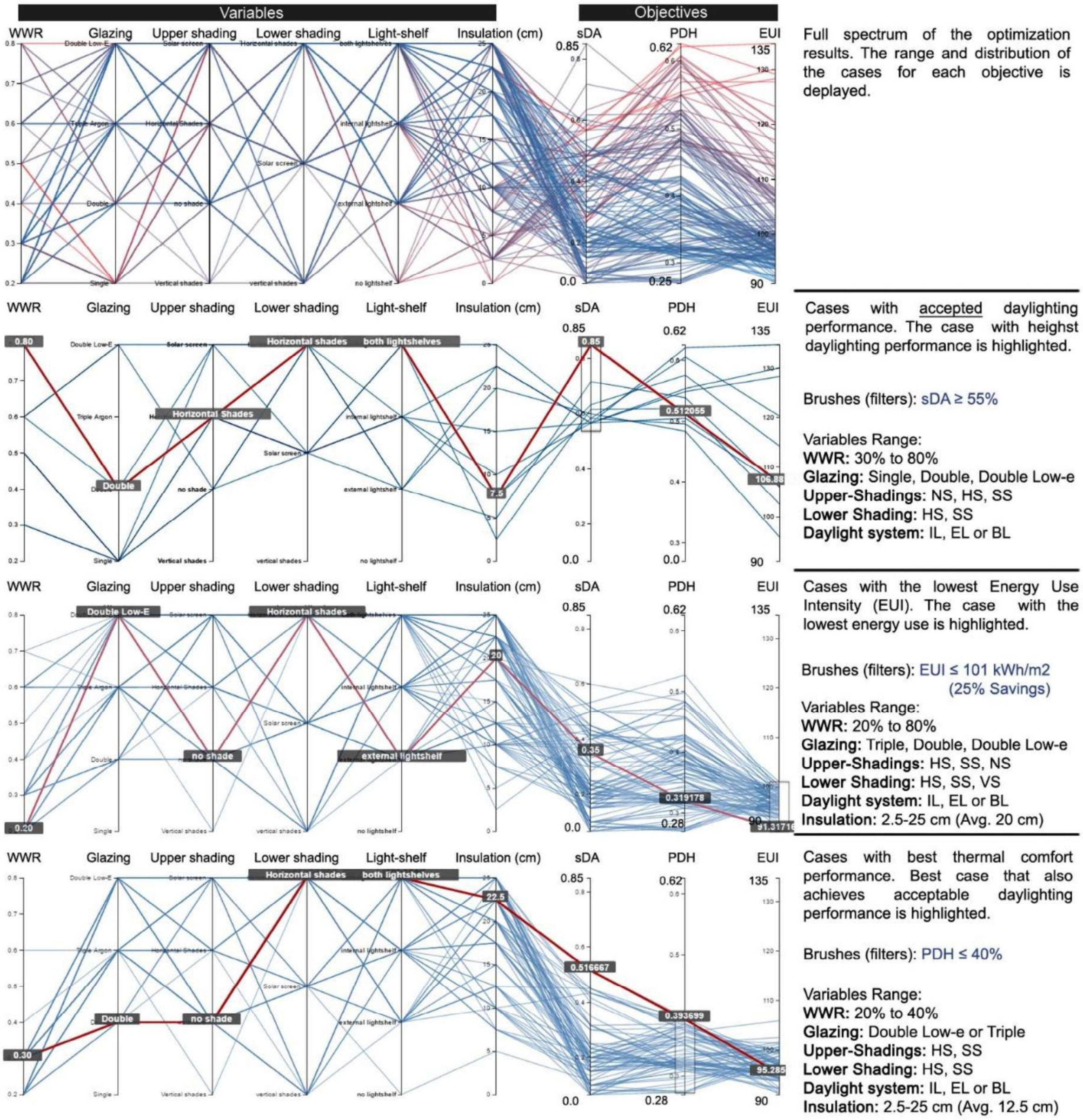

Figure 4 Parallel coordinates plots for the simulated and most performative cases for each objective in Munich

Table 5 Design variables and objectives values for Pareto-optimal solutions in Munich.

WWR	Glazing	Upper-Shading	Lower- Shading	Light-shelf	Insulation (cm)	sDA (%)	PDH (%)	EUI (kWh/m2/yr)
0.60	Triple Argon	No shade	Horizontal	Both	22.5	52%	40%	92.33
0.30	Double	No shade	Horizontal	Both	22.5	52%	39%	95.29
0.60	Double Low-E	Solar screen	Horizontal	External	20	60%	48%	95.77
0.60	Double Low-E	No shade	Solar screen	Both	2.5	62%	52%	102.44
0.80	Double	Horizontal	Horizontal	Both	7.5	85%	51%	106.88
0.30	Single	No shade	Horizontal	Internal	15	57%	51%	107.09

Thermal comfort

Thermal comfort was enhanced gradually, yet enhancements were mainly connected to the reduction in the WWR. That resulted in an inverse proportion relation between daylighting and thermal comfort. As a result, despite the PDH reached a minimum of 27%, cases that achieved acceptable daylighting had a minimum of 40% PDH. Further enhancements for the HVAC system might be needed in this case.

Pareto-optimal

Thirty-one Pareto-optimal solutions were produced from the optimization. However, only six cases achieved an acceptable sDA with variety of design variables. Table (5).

DISCUSSION AND CONCLUSION

This paper investigated the use of a multi-objective optimization framework to arrive at high-performance façade designs. A parametrically modelled office facade was optimized for the climate conditions of Cairo and Munich. The objectives of the optimization were enhancing the daylighting performance, energy use and thermal comfort. Several passive strategies were used as the optimization variables.

The results showed the capability of the process to provide diverse design alternatives with enhanced performance in both case studies. Reduction in energy use reached more than 30% in both cases, while the daylighting performance reached adequate levels with a maximum sDA of 100% and 85% in Cairo and Munich respectively. Thermal comfort was also improved considerably compared to the base case, but remained within unsatisfying level in most cases. Since the cases were assumed to be fully air conditioned, the HVAC system might also need to be optimized for further enhancement in thermal comfort.

General trends were found to emerge from the results which also coincide with previous research. The effect of wall insulation was obvious in both cases and played an essential role in reducing the energy use. Similarly, high performance glazing and in particular the double glazing with low-e coating was present in most of the successful cases. The use of shading devices was more effective in the case of Cairo and facilitated the use of windows with considerably higher window-to-wall ratios. This can be explained in the light of the excessive presence of sunlight in Cairo where the shading devices and high glazing succeeded in blocking the direct sunlight and reducing solar gain and therefore keeping the cooling loads at almost constant level. Concurrently the large glazing area benefited from the available diffused lighting in reducing the lighting load and hence the overall energy consumption. On the other hand, in the case of Munich, lower window-to-wall ratios had better energy performance, as savings from the use shadings and high-performance glazing could not match the increase in heating load due to the high window-to-wall ratios. Light-shelves were found to be always useful and were hardly absent in all successful solutions in both cases.

In conclusion, it became apparent that the use of multi-objective optimization for complicated design problems can aid at reaching performative solution and clarify the relation between the design variables and objectives. The effect of the different variables on each objective can be separately and thoroughly analysed, while trade-offs and overall performance can also be investigated. The main downside of the optimization process lies in the duration of computation time. The optimization process for each of the two case studies consumed nearly 48 hours on a desktop computer with 1.6 GHz i7 processor and 6 GBs of RAM. The coupling of the optimization tool with different simulation engines and software limited the use of parallel implementation and didn't utilize the full computing power. This can be a serious obstacle specially when considering more complex design problems and much larger number of design solutions. Using surrogate models or parallel implementation can enhance the framework. The continuous improvements in both optimization and simulation tools, potential for further research is apparent in the diversity of design problems that could be defined and the endless number of variables and objectives that could investigated.

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A Visualization Dashboard and Decision Support Tool for Building Integrated Performance Optimization

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Analyzing the results of multi-objective optimization and building performance simulation can be a very tedious process that requires navigating between different software and tools. There is a clear scarcity in visualization tools that combine methods for big data analysis and design decision support tools that integrate detailed information for each design and parameter. Having a single visualization tool that provides methods to both visualize and analyze a large amount of data, understand the relation between objectives and variables, and having the ability to compare and analyze the preferred designs thoroughly can support the process of design decision making. In this paper, previous attempts to develop better data visualization tools for both integrated building simulation and optimization outputs were analyzed, then guidelines and a visualization tool prototype that can be effective in decision making and analyzing multi-objective optimizations results was presented.

Keywords: *Multi-objective optimization, Building Performance Simulation, Simulation, Visualization tools*

BACKGROUND

Due to global climate change and the related risks and challenges, the need to reduce carbon emissions is more obvious than ever. Planners, architects, and engineers are the key players to create a more environmentally friendly and sustainable built environment. Building Performance Simulation (BPS) is an important tool to support the move towards more energy efficient buildings and is becoming an integral part of the current design decision-making process. BPS software and tools are being rapidly developed to be more user-friendly and accurate. Despite the high demand for more user-friendly interfaces, simulation results' visualization and analysis tools are not usually given the deserved attention.

Decision-making and data visualization tools have a great impact on the final design product. In a recent survey, nearly 25% of participants (architects and engineers) identified graphical representation as their top priority for the user interface of BPS software (Attia et al., 2009). However, another survey showed that most users were not satisfied with the Graphical User Interface (GUI) offered by commercially available tools. In the survey, 75% of the users pointed out the lack of a graphic interface for post-processing of the BPS optimization results (Attia et al., 2013). As a result, most of the surveyed users had to depend on their own post processing skills or self-developed tools to graphically present the simulation output, and analyze the data.

The scarcity of efficient data analysis and insufficient quality of visualization tools is even more evident in the case of an integrated (holistic) assessment or a multi-objective optimization. In an integrated design assessment, it can be necessary to have a dashboard that gives an overview of all the relevant performance aspects, and summarizing the performance of the building while simultaneously provides detailed information where needed. On the other hand, analyzing a large number of simulation outputs, such as results from a multi-objective optimization, requires more advanced tools to examine the whole set of data and to find relations between different objectives and variables. For multi-objective optimization of integrated building performance, there is no single visualization tool that combines methods for big data analysis and design decision support through detailed information for each of the relevant aspects. As a result, analyzing the multi-objective optimization results becomes a very tedious process and requires navigating between different software and tools. A single tool, that provides methods for analyzing and visualizing a large amount of data, clarifying the relations between objectives and variables, and having the ability to compare and analyze the preferred designs thoroughly, can support the decision-making process.

This paper presents guidelines and a preliminary prototype of a visualization tool that can effectively support the decision-making in multi-objective optimization. In a first step, existing attempts to develop better data visualization tools for both integrated building simulation and optimization outputs were reviewed and discussed. In a second step, effective techniques for the creation of a data visualization tool that can aid in the decision-making process were presented. And finally, a prototype of a visualization tool was brought forward as a proof of concept.

PREVIOUS WORK

Analysis of optimization results

Several research works investigated the analysis of building performance optimization results. Brownlee and Wright (2012) sought to analyze the relationships between design objectives and variables, using a simple ranking order and correlation coefficient. They used a combination of scatter plots and spreadsheets to graphically present the optimization results. Scatter plots accompanied by parallel coordinates graphs and graphic images were also used by Chaszar et al., (2016). Such graphs provided useful feedback, but it was noted that adding more interactive capabilities could further enhance the workflow. To help designers better understand the optimization results, Wortmann (2016) presented a novel method to represent the results graphically. His method, called Performance Map, helps in identifying the optimization problem, relating parameters and performance, examining promising designs, and guiding automated design exploration. Other effective methods were also addressed in other engineering disciplines (Pryke et al., 2007; Witowski et al., 2009). Nevertheless, while these methods can simplify analyzing a large number of cases, it does not provide detailed information on each performance aspect. For instance, while using scatterplots and parallel coordinates graphs can aid in finding an optimal design for daylighting performance, it does not show how the daylight is distributed within the space, or at which hours artificial lighting is needed. Such detailed information and context are necessary for the decision-making process. The ability to examine and compare several aspects at the same time is also equally important.

Integrated performance dashboards

The importance of integrating graphical representations of diverse performance analysis in a single dashboard was highlighted by many researchers. The Daylight-Europe project (DLE) presented the "Integrated Performance View (IPV)", a multi-parameter dashboard to compare reference and as-built cases

(Hensen et al., 1996). This dashboard proved useful in comparing the overall performance of design cases, as it integrated different charts and graphs for heating load, energy consumption, visual comfort, thermal comfort and glare index.

The IPV tool was further developed to provide more flexibility and customization as well as several enhancements for better communication with users (Prazeres & Clarke, 2005). Struck et al., (2012) built upon this concept with a special focus on human cognition and more innovative graphs, such as temporal maps and motion charts. Other research works and commercial software also offer an integrated performance dashboard. However, most of these tools lack the ability to deal with a large amount of data, and thus cannot be efficiently used to analyze the results of multi-objective optimizations.

INTERACTIVITY AND VISUALIZATION TECHNIQUES

Information visualization can be defined as "the use of interactive visual representations of abstract data to amplify cognition" (Ware, 2012). Scientific research on information visualization has resulted in several best practices and guidelines for visualization design (Cleveland, 1985; Few, 2006; Tufte, 2001; Ware, 2012). Interactivity plays a major role in the visualization tools. Yi et al., (2007) presented seven interactive techniques that can be effectively applied to the case of building performance optimization. The first four techniques, Select, Explore, Reconfigure and Encode, can help the user explore the whole set of data by switching between different graphical representations of data and marking preferred designs. The other three techniques, Abstract/Elaborate, Filter, and Connect, can be used to provide detailed in-

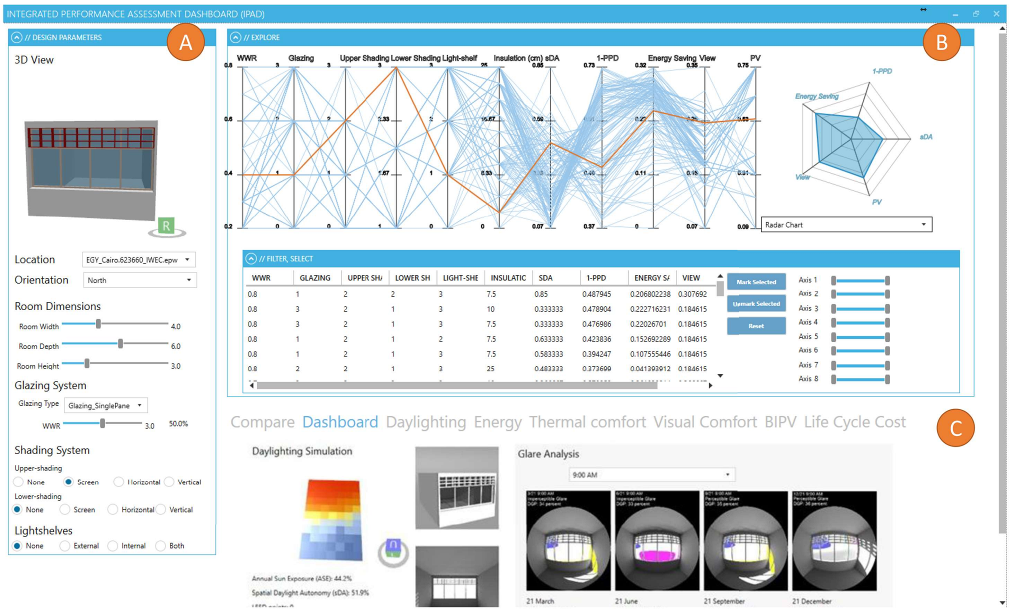


Figure 1
A screenshot of the visualization tool. A- Context and design parameters panel, B- Explorer panel, and C-Integrated dashboard

formation for selected cases. Adding two other techniques, such as Compare (for directly comparing selected cases) and Advice (as a tool for guiding further enhancements) allows for quick, yet thorough, comparison between preferred cases and supports informed decision-making. These two additional techniques were also suggested by Haeb et al. (2014), who highlighted the importance of spatial context and visual feedback as an essential component in the field of building performance simulation.

VISUALIZATION DASHBOARD: GUIDELINES

Building on the reviewed literature, the following guidelines, and requirements for a new tool for visualizing the results of integrated building performance optimizations were defined. The suggested visualization tool can provide better ways to investigate the building optimization results by offering three levels of data analysis:

1- Design space overview and exploration

At the first level, the full set of simulation results should be explored. Multi-dimensional graphs, such as parallel coordinates and scatter plots, are useful in this case. Switching between plot types, filtering the results and selecting favorite cases help in clarifying basic relations between the objectives and variables, in addition to highlighting optimal and preferred designs.

2- Sensitivity analysis and parameter relations

On the second level, the direct relation between any two variables or objectives can be investigated. The use of sensitivity analysis and 2D charts can indicate the variables that drive the optimization process, the expected enhancement in each objective, and the relative importance of the design variables.

3- Detailed results and comparison between favorite designs

At the final level, an integrated dashboard is presented with detailed performance data, which provides all the needed information about each selected design. To ensure an informed decision-making process, the visualization tool should offer the ability to compare the detailed performance and contextual reference (images and 3D model of the cases) of favorite cases.

VISUALIZATION DASHBOARD: PROTOTYPE

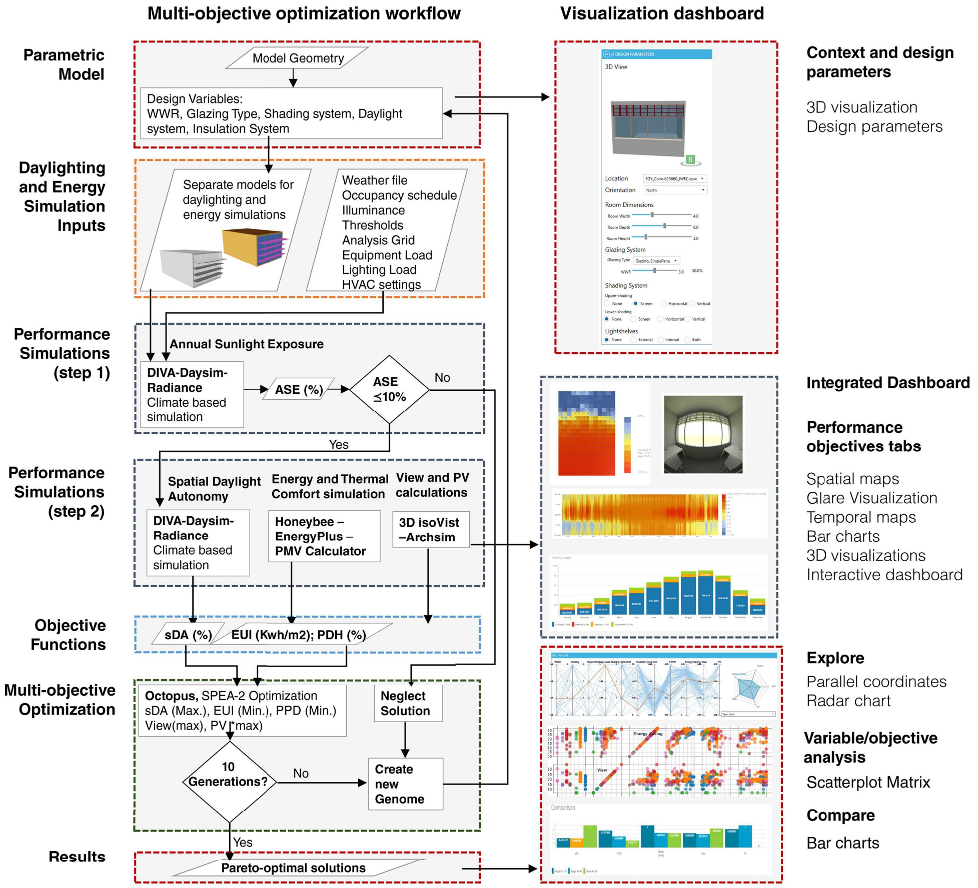
As a proof of concept, a preliminary prototype was developed according to the above-mentioned guidelines. The prototype was built using the visual language programming tool Grasshopper and HumanUI, a plugin for Grasshopper that enables the creation of graphical user interfaces. Additional Grasshopper user objects and code functions were written to overcome limitations in the HumanUI Plugin. The visualization tool consists of the following panels.

Context and design parameters. The left panel shows the names of the selected design alternatives as well as a zoomable and rotational 3D visualization and the corresponding design parameters. The user can change the design parameters to specify they design alternative (Figure 1-A).

Explore. Alternatively, the user might choose to select the design from the Explore section. The Explore section contains a parallel coordinates chart that shows the design variables and results of the complete design set with the selected design highlighted. Additionally, it also contains a radar or bar chart for showing the performance of the selected design as well as a data table. The user can filter the design alternatives by limiting the values of any of the variables or the objectives. It is also possible to mark cases in order to be compared later to each other (Figure 1-B).

Variable-objective relations. In this panel, the user can choose a variable(s) and objective(s) to see

Figure 2
The workflow of the optimization process and the corresponding visualizations panels in the visualization tool.



the direct relation between them, which is rendered in the shape of a 2D scatterplot chart in the case of a single variable and single objective, or as a matrix of scatterplots in the case of several variables and objectives.

Compare. The compare panel offers a bar chart to compare the marked design alternatives as well as simple visualization of each performance objective.

Integrated Dashboard. Similar to the IPV tool discussed earlier in the literature, the integrated dashboard houses more details for all the performance objectives for the selected design alternative.

Performance objectives tabs. For each performance objective, a separate section that includes alternative ways of result visualizations an even greater detail of result analysis is provided.

To make it easier for the user to explore and choose preferred designs, the ability to show or hide

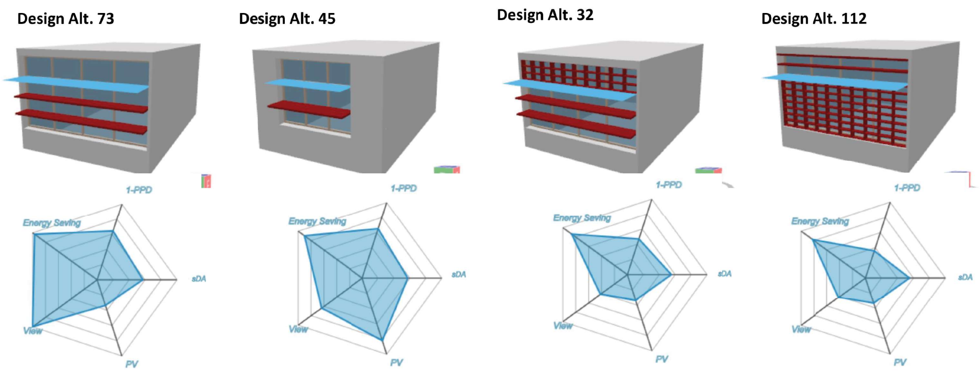


Figure 3
Different design alternative with similar energy savings.

panels was provided. This enables the user to focus on a specific panel or several ones, e.g., the Explore & Integrated Dashboard or the Explore & Compare. Figure 1 shows a screenshot of the visualization tool prototype with three active panels: Context and design parameters, Explore and Integrated Dashboard.

CASE STUDY

The visualization tool prototype was used to visualize the results of a building performance optimization, in which a parametric model was optimized for the integrated performance of the following parameters: Energy consumption, Daylighting, Thermal Comfort, View and Glare and Renewable Energy. The parametric model was built using Grasshopper. EnergyPlus [1] and Radiance simulation engines, used through the HoneyBee (Roudsari, M. S. & Pak, M., 2013) and Diva (Jakubiec, J. A., & Reinhart, C. F. 2011) plugins, were utilized for the energy and daylighting assessments. A multi-objective optimization was carried out using the optimization tool Octopus (Vierlinger, R., & Hofmann, A. 2013).

Parametric model

The optimization was carried out for the south façade of a single office space in Munich, Germany (48°8′N 11°34′E). The office room was assumed had the dimensions of 4.00m x 6.50m x 3.00m for the width, depth, and height, respectively. The parametric model of the south façade provided different settings for the glazing area, glazing system, shading, daylighting system, and insulation system. The glazing area was divided into upper and lower parts, where the upper part acted as a clerestory window. Both window parts were introduced to the shading devices separately. Seven Window-to-Wall Ratios were studied together with four glazing systems, four shading systems, and four light-shelf settings. Additionally, the building insulation was increased gradually with 2.5 cm steps to a maximum of 25 cm. Overall, nearly 20,000 design alternatives can be generated.

Multi-objective optimization Workflow

A multi-objective optimization was performed with the evolutionary algorithm SPEA2 using Octopus. A random generation was created at first, which contained different cases (genomes). Then for each

Figure 4
Scatterplot matrix chart showing the relation between energy savings, insulation and glazing type.

genome, daylighting, energy and thermal comfort analysis were carried out using DIVA and Honeybee. At the same time, the openness of the façade to the view outdoors and the possible area for building integrated photovoltaics was calculated. The results from the analysis phase were used as the fitness values for the optimization, namely the spatial daylight autonomy, energy savings compared to an unshaded base

Figure 5
Examples of the contents of the performance tabs. A- Energy use analysis. B-Daylighting performance analysis. C- Thermal comfort. D- Visual comfort (Glare and View). E- The compare tab showing a simple comparison of three selected cases.

case, the percentage of comfort hours, view and PV percentages. The optimization process continued for 10 generations with a population size of 30. The mutation rate was set to 0.5, the mutation probability to 0.1 and the crossover to 0.8. Cases with very high solar exposure were neglected.

During the analysis, the results from the simulations were post-processed into different types of visualizations according to the results type. After the optimization ends, the optimization results are also visualized using parallel coordinates and scatter plot charts. Figure 2 shows the workflow of the optimization process and the corresponding data visualization in the prototype.

Optimization results analysis

The optimization resulted in 150 design alternatives. The results were analyzed in several ways using the visualization tool prototype. First, the results and parameters of all the 150 cases were analyzed using the Explore section. The parallel coordinates chart offers an interactive tool by which the results could be filtered for a specific range of values for any and each of the variables and objectives. Additionally, the results in the data table could be sorted for any of the variables and objectives. A radar chart for the objective results is also shown for the selected design alternative. In this case study, the design alternatives were sorted for highest energy savings. It was found out that several design alternatives achieved energy savings between 30-32%. Although these cases achieve a similar energy performance, their design parameters and other objective performances differed greatly. Only one alternative, for instance, achieved an acceptable daylighting performance value (sDA more than 50%). This enables the designer to choose his design wisely by taking all the objectives and also the design features in mind. A trade-off between the different objectives is of course necessary. Figure 3 shows the four design alternatives with the highest energy savings and a minimum daylighting performance of sDA= 50%. Their corresponding performance for the other objectives is illustrated using the radar chart.

In a second step, the relation between variables and objectives can be studied using scatter plots matrix in a separate window. For instance, the scatter plot between the energy savings and glazing and insulation shows how triple glazing and double low-E glazing have a higher potential for energy savings compare to single and conventional double glazings. For the insulation, it could be noted that the potential for energy savings increase with the increase of the thickness of the insulation. Nevertheless, most of the cases with 10 cm insulation were able to achieve energy savings between 25% and 30% (Figure 4).

To compare the performance of the preferred designs, marked cases are automatically added to the compare panel, where a simple bar chart comparison is created. Finally, the integrative dashboard and performance tabs show detailed and alternative visualizations for each of the optimized objectives. Other simulation outputs can also be investigated such as lighting and occupancy schedules; heating, cooling and equipment's load; alternative daylighting performance metrics like the daylight autonomy, daylight availability, ... etc.; glare analysis for various times and dates; ... etc., Figure 4 shows part of the different tabs for a single design alternative and the compare tab with a comparison between the cases with the highest daylighting, energy and BIPV area (Figure 5).

CONCLUSION AND DISCUSSION

Energy efficient and sustainable buildings are slowly, but surely, becoming the standard in architecture and building practices. As building performance simulation software and optimization tools become more common in the building design process, it is vital to have an integrated result analysis and visualization tool to support the design decisions. This paper presents a prototype for a visualization tool that can help analyze the results of building performance multi-objective optimizations. The visualization tool aids in investigating the whole design set, analyzing the relation between variables and objectives, as well as comparing and further investigating preferred designs. As a result, the user can define areas with potential enhancements, find the most effective design variables and compare the integrated performance between different designs in a visually-informative way. By achieving these different functions, the tool can help in the design decision process by shortening the time required to analyze the vast amount of data resulting from multi-objective optimization. In future works, other enhancements could be investigated, such as building the tool with a more sophisticated programming language like Python or Java, supporting dashboard customization, and validating the tool by focus groups. Implementing a guiding system can also be a valuable addition to the prototype to ensure that an optimal performance is reached by showing possible areas of enhancement.

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Optimization of Facade Design for Daylighting and View-to-Outside

A case study in Lecco, Lombardy, Italy

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Minimizing the impact of shading devices on the view to the surrounding view is essential for indoor spaces that overlook exceptional scenery and views. Building facades that overlook such views require a special care not to obstruct the view to the outdoors. At the same time, poorly designed shading devices can result in high solar penetration and glare probability affecting the ability of the users to enjoy the outdoor view. In this paper, we analyze the effect of adding different shading devices and configurations to a south façade for a workshop space in Lecco, Italy. A parametric model of five types of shading devices was analyzed for the daylighting, glare and view performance. The trade-off between the objectives and the cases that achieved satisfactory performance in all three criteria were presented.

Keywords: *Computational design, Daylighting, Optimization, View to outside*

INTRODUCTION

This paper presents the result of an evidence base design project, for the Sustainable Building Technologies (SBT) course and studio of Architecture Design (AD), a mandatory course in architecture and building engineering master degree in Politecnico di Milano, Lecco campus. The multi-disciplinary design project aims to understand the integration between architecture, energy efficiency and construction technology, to apply innovative construction technologies and critic it per architecture design requirements.

The project's goal was to design a multi-functional building located in La Piccola area, in the historical industrial area of Lecco city, in Lombardy, north of Italy. The building's site is in front of the new campus of Politecnico di Milano. Site reconfiguration and the absence of residential complexes left the site with an unobstructed panoramic view of the surrounding mountains. The proposed design consists of three floors plus a ground floor with various functions related to the Politecnico di Milano, such as: sports center, library, study areas for students, auditorium, food court connected to the Lecco Market, and space for workshops with 150 m2 area. The workshop space covers most of the fourth floor. In order to provide a 360° panoramic view of the surrounding mountains, the fourth floor has floor-to-ceiling

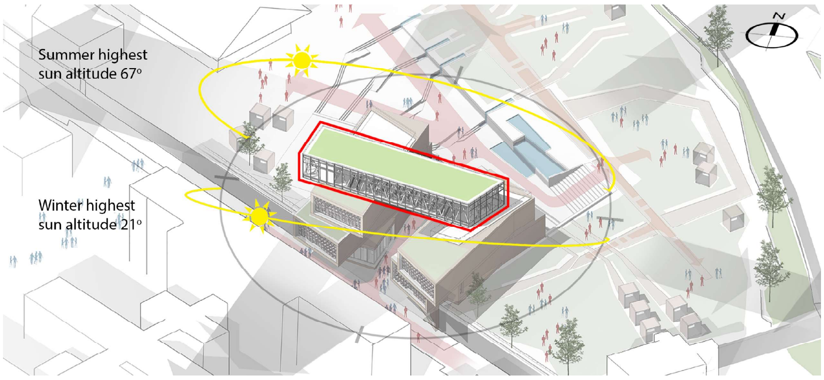


Figure 1
Project Location and Building configurations in the site. the diagram shows the orientation of the third floor with the sun altitude

windows in all four orientations. This left the space, however, vulnerable to direct sun penetration. (see Figures 1 and 2)

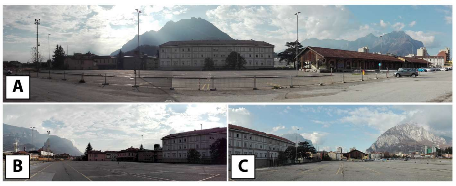


Figure 2
Panoramic view from the project site. Image (A), toward the south direction. (B, C) toward south west and east

Therefore, the biggest challenge facing the proposed project was to keep the view from inside to outside with minimum obstruction in all the directions while providing sufficient daylighting and minimal glare. The studied floor had a rectangular shape with the long sides having a North-South axis with a tilted angle of 10°, and the short sides facing East and East. While the North, façades don't receive high sun exposure for most of the day, the South façade is subject to high exposure for most of the day, throughout the year. East and West facades had a small impact on the daylighting performance of the space due to their relatively small area and being separated than the working space by the staircase and elevators cores.The four façades, especially the south, overlooks the best landscapes of Lecco since it looks directly on historical Lecco's mountains, Resegone, San Martino, Monte Moregallo, Grigna Settentrionale e Meridionale and Monte Barro. Hence, the importance of creating a 360° panoramic view while providing enough daylight for the workshop space. (see Figure 3)

The city of Lecco has a humid subtropical climate, with hot and humid summer and cold winter. The highest sun altitude in winter is of 20.8°, while in summer 67.4°. Moreover, the solar radiation can rise to 1600 kWh/m2 per year. The temperature rarely goes far below zero Celsius, the winter conditions nonetheless require non-negligible heating systems for the comfort. On the other hand, in summer, the high humidity and temperatures (often rising over 25° Celsius from June to August) require an equally important cooling load. As the air flow rate through the year is not adequate to provide natural ventilation, special attention for cooling and heating loads is necessary. Conventional design methods of passive techniques such as shading devices like horizontal shades, Venetian blinds and screens were historically used especially in south facades to reduce the sun exposure, provide adequate daylight and to reduce the glare probability.The concerns in using this kind of shading device are that it doesn't implicate the view factor to outside as a driving force for the design. Therefore, a trade-off between the different measures has to be reached in order to achieve a visual comfort and preserve the view of the surrounding alpine landscape. This paper discusses the relation between the two parameters (daylight and view) by applying daylighting and glare analysis as well as view assessment of different shading devices.

Figure 3
Visualisation for the case study.
showing the usage of the interior space beside the southern facade.

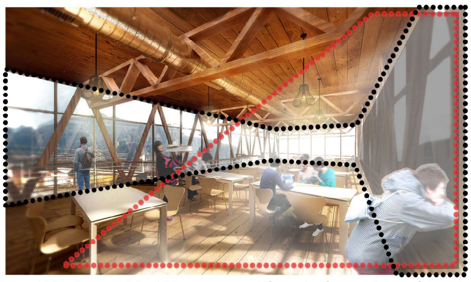
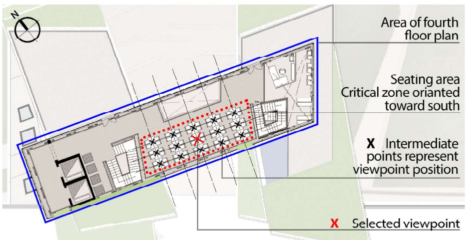


Figure 4
Third-floor plan. As shown the "critical" area of investigation - the workspace - with applied grid for setting intermediated points of examination.



PREVIOUS WORKS

Shading devices were historically used to reduce the negative effects of direct sunlight and solar radiation inside buildings during cooling period and to permit heat gains during heating (Platzer, WJ.,2001). The impact of using traditional shading devices such as horizontal louvers and solar screens on daylighting, energy use and thermal comfort was studied by several researchers in different locations and climates. Yoo S, et al., (2011) investigated the usage of fixed shading devices on decreasing the thermal loads in addition to increasing the visual comfort and decreasing the glare, and, it was found inevitable to use it on the south facades, especially in Mediterranean climates. In a similar approach, Datta G. (2001) studied the thermal performance of a building with external fixed horizontal louver with variable slat lengths and tilts. LIGHTSCAPE software and PHOENICS Computational CFD package for natural ventilation were used by Hien and Istiadji (2003) to study the effects of 6 different shading device types on thermal comfort in a residential building in Singapore. Hammad and Abu-hijleh (2010) analyzed the energy consumption of external dynamic louvers integrated to office building's facade in Abu Dhabi. The impact of using different shapes of solar screens on daylighting and energy performance in hot arid climate was investigated by Sherif et al. (2012). Parametric and generative design tools allowed the creation of shading devices with a higher degree of geometrical complexity. El Ahmar et al., (2015) used a double skin facades inspired from nature to design a porous and folded façade for reducing cooling loads while maintaining daylight needs of office buildings in hot climatic regions. The possibilities of different arrangements of folded modules had been also examined to create environmental efficient kinetic morphed skins, to achieve different Kinetic origami-based shading screens categorized parametrically to provide suitable daylighting (El Ghazi et al. 2014).Kirimtat et.al, (2016) conducted a review of previous research work that utilized simulation modeling to analyze the impact of shading devices. More than a hundred paper were analyzed and organized by simulation type. Different types of simulation analyses were studied including the overall energy performance, daylighting, natural ventilation, indoor thermal and visual comfort among many others. However, it can be noted that only a few studies considered the view as one of the main objectives of shading devices design (Tzempelikos A.(2008), Kim & Kim (2010), Sherif et al. (2016)).

View to the outside is more than often left out during design, despite the undoubted importance of view and effects on users (Leather et al., 1998; Heschong Mahone Group, 2003), Hellinga and Hordijk (2014) attributes this to the reasons that research on daylighting and view quality belongs to different research discipline and secondly, there is usually very limited time and budget for architects and engineers to work on daylighting and view. Hellinga and Hordijk also found that users prefer distant and nature views and views that contain water. In design cases were view is an essential concern, such as spaces overlook-

Shading type	Parameters	Range
Horizontal shading	Vertical Shading Angel (VSA)	20° to 50° with a step of 5°
Vertical shading	Horizontal Shading Angel (HSA)	20° to 50° with a step of 5°
Eggcrate	Vertical Shading Angel (VSA) Thickness	20° to 50° with a step of 5° 2.5 to 12.5 cm with a step of 2.5 cm
Diagrid structure	Vertical Shading Angel (VSA) Number of Modules (Spacings)	20° to 50° with a step of 5° 6, 12, 18, 24 and 30 Modules
Diagrid structure + overhang	Vertical Shading Angel (VSA) Number of Modules (Spacings)	20° to 50° with a step of 5° 6, 12, 18, 24 and 30 Modules

Table 1
The studied shading devices and its parameters

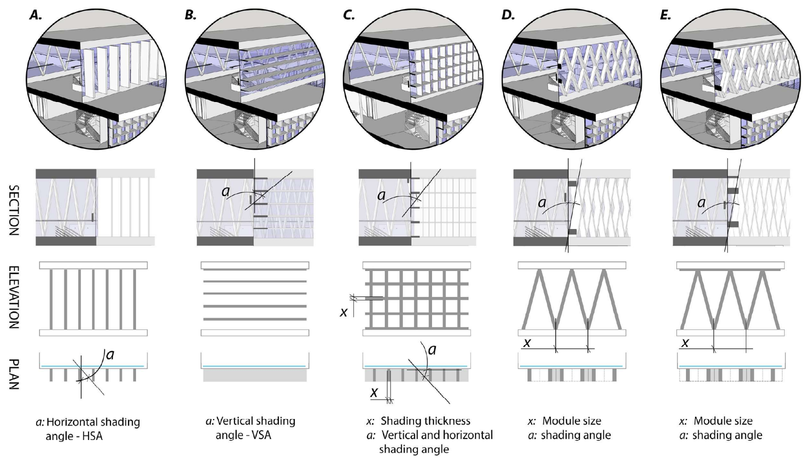


Figure 5
Main designed shading system selected. A.Vertical louvres. B.Horizontal louvres. C.Eggcrate. D.Diagird louvres. E.Diagrid with horizontal louvres. For each, the most effective variables were identified. represented in “modular size”, “shading angle” and “shading thickness”

ing important landmarks or natural features, such as the case presented in this paper, view to the outside cannot be neglected.This paper, therefore, tries to answer the question of How to design a shading system that ensures excellent daylight performance with minimum sacrifice of the view? In the design, utilizing computational and parametric tools to evaluate and optimize the shading systems for daylight and view quality.

METHODOLOGY

PARAMETRIC MODELLING

A parametric model for the multi-functional building was created using the Building Information Modeling software Revit. In order to have a greater control on the design parameters, the model was then exported to, and modified by, a visual programming language for parametric design Grasshopper. The investigated space, which is located on the top floor of the building, had the dimensions of 7.5 m x 20.0m with 3.3m ceiling height. Different types of shading devices were investigated for the daylighting performance, glare probability and view to outdoors. The performances of five shading devices were examined: horizontal shadings, vertical shadings, egg crate, an external diagrid structure, and an external diagrid structure with an overhang. For each of these shading devices, the impact of changing the vertical (or horizontal) shading angle was studied. The impact of changing the eggcrate thickness and spacing for the diagrid was also considered. Figure 1 shows an illustration of the five shading devices and their design parameters. 7 different cases for each of the horizontal and vertical shadings were studied and 35 cases for each of the other three shading devices. Overall 119 shading designs were examined. The ranges of the shading devices parameters that were examined are shown in Table 1. (see Figure 4)

SIMULATION METHODOLOGY

Daylighting analysis was carried out using DIVA for Rhino, which is used as an interface to Radiance and Daysim simulation engines. The criteria used for evaluating the daylighting performance was the daylight availability which was found more suitable to the studied case. The DAv divides the measuring nodes according to three criteria daylit for points that receives illuminance between 300-3000 lux for 50% of the time, over lit for points that receives >3000 lux for at least 10% of the time and partially daylit for points that has illuminance values<300 lux for more than 50% of the time. The aim is, therefore, is to increase the daylit area of the space. The analysis grid had a desk-level height of 0.80 m and spacing of 0.60 m. (see Figure 5)

Glare and view analysis were conducted for a selective viewpoint that represents a seated person (height = 1.2m), 2.0 m from the facade and facing the window. For Glare analysis Evaglare was used to measure the discomfort using the Daylight Glare Probability (DGP) index. the GDP was analyzed at 9:00, 12:00 and 15:00 on the solstice and equinox dates to cover the different sun positions. In the DGP index, glare is divided into four categories: intolerable glare (DGP > 45%), disturbing glare (45% > DGPP 40%), perceptible glare (40% > DGPP 35%), and imperceptible glare (DGP < 35%). In this study, each category was given a score number with imperceptible glare having the highest score (3 pts) and intolerable glare the least (0 pts). the Accumulative Glare Percentage (AGP) is then calculated to compare the performance of different shading designs, where the highest possible value (100%) means that only imperceptible glare occurs at all times and the least (0%) indicates that an intolerable glare can be witnessed at all times.

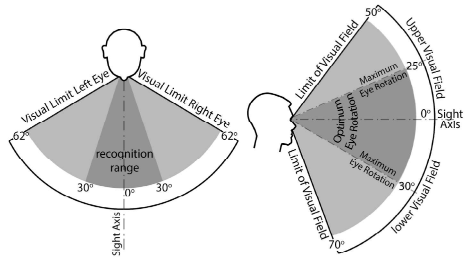


Figure 6
Diagram of the human cone of vision. showing the limit of the visual field and the area of recognition, in two directions, horizontally and vertically.

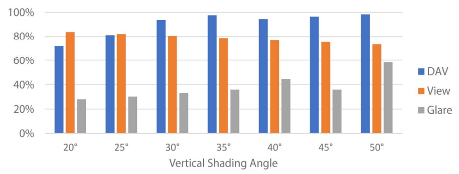
For the view analysis, a view factor was calculated using 3D isovist. An isovist field is defined as ".. the set of all points visible from a given vantage point in space and with respect to an environment." (Benedikt, M. L.1979) . In this study, the vantage point is the same one defined for the glare analysis. A 3D isovist was created for the focal area of the viewer's field of view (see Figure 6). The ratio between the number points seen from the vantage point in each case to that without a shading device is calculated to compare between the different shading devices.

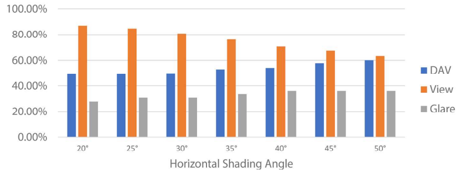
The results from the three analysis criteria, daylighting performance (DAv), Glare (AGP), and View Factor are compared to arrive at shading devices with a satisfactory performance. Acceptable values for the three criteria were assumed to be 75%, 50% and 50% for the daylight availability, accumulated glare percentage, and view factor respectively.

RESULTS

BASECASE

The unshaded facade was assumed as the basecase in this study in order to evaluate the effect of each shading device on the daylighting, glare and view performance. The basecase had a significantly low daylighting and glare performance due to the vast area of unshaded glazing in all its four facades. Due to the penetration of direct sunlight the daylit area reached only 36%, while the overlit area occupied almost two-thirds of the space. The accumulative glare score was found to be very low with a value of 13% as an intolerable glare was witnessed in most of the cases with the exception of the morning hours. however, even at this times, a perceptible or disturbing glare was witnessed. Although the basecase has a panoramic view with only the internal structure as a physical obstacle, such a high probability of glare occurrence and sun penetration would surely affect the possibility of enjoying the view.





HORIZONTAL AND VERTICAL SHADINGS

The horizontal shading devices enhanced the daylighting performance greatly were most of the cases had over 90% daylit area percentage, in comparison to just 36% in the basecase. The glare analysis, however, showed a high probability of glare occurrence and only one case achieved an AGP higher than 50%. The impact on the view was, however, better than anticipated with only between 17% to 27% of the view obstructed. Cases with larger extrusions (higher shading angles) had a better daylighting and glare performance while cases with smaller extrusions had a better view factor.

In contrary, vertical shadings provided a poor but mostly acceptable daylighting performance. The daylit area percentages ranged between 49% with a Horizontal shading angle = 20°, and 60% with HAS= 50°. Glare analysis also showed a high probability of glare occurrence all year round with a maximum accumulative score percentage of 36%. Nevertheless, the view factor was also found acceptable in all the cases with a maximum view factor of 87% and a minimum of 64%. Figures 7 and 8 show the daylighting, glare and view performances of the horizontal and vertical shadings.

EGGCRATE

Thirty-five cases of eggcrate shadings were analyzed. Almost all the cases achieved over 80% daylit area and half of the cases reached 100% daylit area. Nevertheless, unlike the horizontal and vertical shading, the eggcrate reduced the chance of glare occurrence significantly. Most of the cases had an acceptable accumulative glare percentage and in few cases the AGP reached more than 80%. This, however, came in the expanse of the view performance. With the eggcrate cells causing a significant obstruction to the view, the view factor was found to be unacceptable in most of the cases. Only cases with very small thickness (high perforation ratio) and small extrusion achieved acceptable view factor. However, in these cases, the glare performance was at its lowest values and was below the acceptance threshold. Only one case achieved an acceptable performance in all the three criteria which had a thickness of 2.5 cm and 35° shading angle.

DIAGRID STRUCTURE

All the 35 cases of the external diagrid structure had a good impact on the daylight performance with a minimum daylit area percentage of 76% and nearly half of the cases with 100% daylit area. Similar to the egg crate, the diagrid structure also enhanced the visual comfort significantly as the glare probability decreased and the AGP reached 100% in several cases. The external view also showed satisfactory performance with a maximum of 85.54% and most of the cases with view factor higher than 50%. Nine different cases achieved a satisfactory performance in all three areas of analysis. Figure 10 shows the performance of the diagrid cases. Cases with acceptable performance in all of the three criteria are highlighted)

Figure 7
Daylighting, glare, and view performances for the horizontal shadings

Figure 8
Daylighting, glare, and view performances for the vertical shadings

DIAGRID WITH OVERHANG

This unique shading solution aimed at combining the positive impact of both horizontal and diagonal shading devices. Once more, 35 different configurations were tested. It succeeded in achieving notable improvements in all of the three criteria. Daylighting performance achieved more than 90% daylit area in all cases with most cases having a 100% daylit area percentage. Glare probability also improved as almost all of the cases had an acceptable performance and AGP reaching 100% in few cases. While not all the cases had a satisfactory view performance, in many cases the view factor had an acceptable value and reached a maximum of 86%. In many cases the daylighting, glare and view were found to have acceptable and significantly improved performances. One notable case was with 45° shading angles and 6 modules of diagrid external structure, where daylit area percentage reached 100%, AGP of 75% and view factor of 71%. Overall 14 different configurations achieved an acceptable performance in all the three criteria.

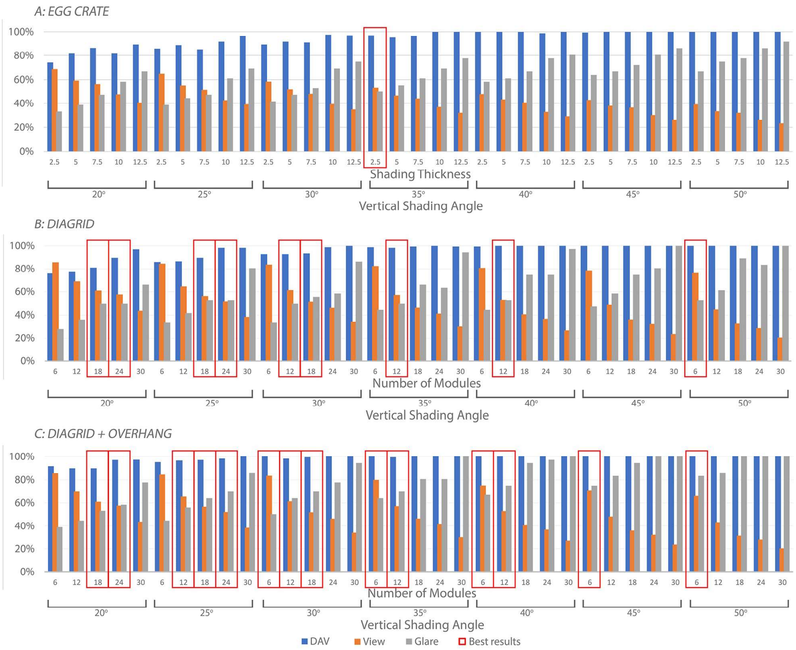


Figure 9
Daylighting, glare, and view performances for the Eggcrate, Diagrid, and diagrid with overhang shadings. The cases with satisfactory performances are highlighted.

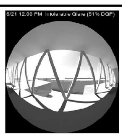
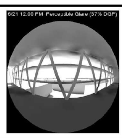
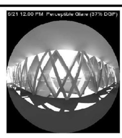
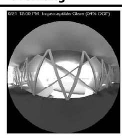
Shading system	Base case	Horizontal shadings	Egg crate	Diagrid	Diagrid and overhang
Glare					
Parameters	*No shading system*	*VSA = 50°*	*Shading thickness = 2.5 VSA = 35°*	*No. of module = 18 VSA = 30°*	*No. of module = 6 VSA = 45°*

Figure 10
Glare performance at 12:00 on 21 June for the base case and four different shading configurations

Figure 9 shows the daylighting, glare and view performances for the eggcrate, diagrid and diagrid with overhang. The cases that achieved an acceptable performance in the three criteria are highlighted. Figure 10 shows the impact of the different shading devices in comparison to the basecase on the glare performance.

DISCUSSION AND CONCLUSION

This paper presented and discussed a design approach for designing building facades that overlook exceptional scenery and views, which requires special care not to obstruct the view to the outdoors. Nevertheless, poor shading design can usually result in high solar penetration and glare probability affecting the ability of the users to enjoy the outdoor view. In this study, 119 different configurations of five shading types were investigated. Overall, 25 different configurations from 4 types of the shading devices achieved a satisfactory performance for daylighting, view and glare. The combined shading of an external diagrid structure and a horizontal overhang offered the best performance with 14 cases, followed by the diagrid shading and eggcrate and horizontal shadings. For future work, and depending on the case study other aspects such as energy consumption, Life Cycle Analysis, and Life Cycle Cost could be included in the framework.

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