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DAYLIGHT COMFORT OPTIMIZATION of EXPANDED METAL MESH SHADINGS

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ABSTRACT

The application of the expanded metal mesh to the building façades has become very common, because of its advantages in building performance; as well as its production and cost-efficiency. As one of the most significant areas of usage being the exterior cladding, the shading properties of it are highlighted. The geometrical properties of it, the crucial ones being the size of the holes, thickness, and the angle of the strips, are affecting the daylight comfort inside the building and can be varied in a wide range within the production limitations. This causes a compelling increase in the construction materials' market, as well as the interest in the field of sustainable architecture.

The goal of this research is to exploit the expanded metal mesh as a shading device within its geometrical parameters; proposing a system where these inputs adapt according to the orientation of the glazed surface and the climate properties of its location. The adaptation will be focused on achieving comfort conditions of illuminance levels inside while proposing the implementation of the sheet to various typologies of surfaces. The methodology is further demonstrated by the optimization operation on case study buildings and three critical surface typologies to confirm and improve the efficiency of the shading system. Satisfactory improvements on the daylight comfort, measured by Customized Spatial Daylight Autonomy, have been obtained by exploiting the geometrical parameters of the expanded metal mesh. The advantages of it is offered within variety of design solutions to the field of sustainable architecture.

Keywords: Computational Design, Parametric Optimization, Sustainable Design, Daylight Comfort, Building Performance Simulation, Grasshopper, Expanded Metal Mesh

SOMMARIO

L'applicazione della rete metallica stirata alle facciate degli edifici è diventata molto comune, a causa dei suoi vantaggi nelle prestazioni dell'edificio; così come la sua produzione e l'efficienza dei costi. Poiché una delle aree di utilizzo più significative è il rivestimento esterno, ne vengono evidenziate le proprietà ombreggianti. Le sue proprietà geometriche, quelle cruciali sono la dimensione dei fori, lo spessore e l'angolo delle strisce, influenzano il comfort della luce diurna all'interno dell'edificio e possono essere variate in un'ampia gamma entro i limiti di produzione. Ciò provoca un forte aumento del mercato dei materiali da costruzione, nonché l'interesse nel campo dell'architettura sostenibile.

L'obiettivo di questa ricerca è quello di sfruttare la rete metallica stirata come dispositivo ombreggiante nei suoi parametri geometrici; proporre un sistema in cui questi input si adattano in base all'orientamento della superficie vetrata e alle proprietà climatiche della sua posizione. L'adeguamento sarà mirato al raggiungimento di condizioni di comfort dei livelli di illuminamento interno proponendo l'utilizzo della lastra a diverse tipologie di superfici. La metodologia è ulteriormente dimostrata dall'operazione di ottimizzazione su edifici caso studio con diverse proposte per la forma della superficie, esaltando il valore dell'autonomia spaziale diurna di uno spazio sottoposto.

Parole chiave: progettazione computazionale, ottimizzazione parametrica, progettazione sostenibile, comfort alla luce del giorno, simulazione delle prestazioni degli edifici, cavalletta, rete metallica espansa

PREFACE

I would like to thank my supervisors, Prof. Andrea Giovanni Mainini and Prof. Tomasso Pagnacco, for leading me in this path as well helping me to improve my knowledge on the field that I am passionate about.

I also would also like to thank my mother, Nese Yuzak for her constant support even in the most challenging times and Marco Enna for helping me in every step of the process while inspiring me for all my decisions.

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INTRODUCTION

The focal aims of the architectural and engineering world have been the issues of sustainable design and energy efficiency due to the climate change problem that the world is facing. These matters have made the new design approaches to gravitate towards the computational/parametric approach. Both in my bachelor’s in architecture and master’s in building engineering, I have encountered many projects in which the optimization of the subjected design element tried to be achieved considering different aspects of the design and construction field. These studies have given me a background on daylight and energy optimization integrated with the building design.

The studies on building façade components are crucial aspects of daylight optimization that, it is highly interesting and useful to analyse the behaviour of different materials as shading devices. Moreover, since the expanded metal mesh is an effective product in the exterior cladding market, the performance of it emerges as a new field of research.

The goal of being able to exploit the characteristic of a material that is commonly used in the field was the main motivation of the thesis, with the opportunity to increase knowledge on the new technologies regarding computational design.

1. Forward

The building envelope components have a significantly high impact on the building’s overall performance, acting as the boundary between the living spaces and the outdoor environment. Both the energy performance and the daylight performance of the building is dependent on the design and the material characteristic of the components that are used. Serious economic and environmental issues emerge due to the excessive heat gains in the poorly designed buildings. [1] That is why daylight design plays an important role in terms of visual comfort and decreasing energy demands.

One of the key elements to support sustainable design where the building envelope is implemented according to the daylight performance of it; is the shading devices. The shading systems protect the internal space from solar radiation and the increase of temperature, allowing an appropriate daylight transmittance and visibility into the interior space of the building. The permeability and the optical performance of the façade plays an important role in the outward vision and privacy protection. Shading devices are responsible for controlling all these aspects together as well as having an impact on the aesthetical appearance of the building. [2]

Expanded metal mesh is one of the leading materials in the construction market due to its efficiency in production and cost. EMM (expanded metal mesh) has been commonly used as a sun control layer on façades, offering good advantages on the thermal and visual comfort. It allows the daylight to pass through in a strategic way, as well as reducing the cooling costs when it is used as a sunshade. Moreover, it is highly effective in blocking the direct sunlight which causes the problem of glare; while allowing an adequate portion of the indirect, eye-friendly daylight through.

Having many advantages as mentioned above, EMM has a high number of parameters which are controlling the daylight performance of it. Moreover, the world of computational design and parametric optimization offers a wide range of possibilities to exploit the characteristics of expanded metal mesh as an exterior cladding.

2. Goal and Scope

The content described above represents the tendency of the main goal of this research to be the achievement of parametric optimization of the daylight performance using expanded metal mesh.

The daylight behaviour of EMM is aimed to be realized within its geometrical parameters, as the primary step of the process. This understanding would lead to a simplification of the geometry to be modelled and controlled in the parametric environment, using Grasshopper supported by Rhino 6.0.

The strategically modelled EMM would be adapted to different typologies of surfaces where it is functioning as a shading system. Simple shoebox models, case study buildings, and designed variations of complex surfaces would be analysed through this adaptation in order to give a wide range of possibilities to the architects and engineers. This adaptation is aimed to be made in a such a way that, the defined geometrical parameters would vary according to the contextual conditions considering the climate, function of the building, surroundings, and the orientation.

The optimization would be aiming to decrease the over-lit areas that create discomfort due to the excessive heat gains as well as making sure the adequate visibility is provided for the users. Obtaining a beneficial database containing optimized daylight performance results of different configurations would be the end product of this research process.

3. Outline

The research will start by introducing both the main material and the main approach that is studies; expanded metal mesh and parametric optimization. The scope of the application areas of EMM would be analysed giving architectural examples and demonstrating the advantages. The goals would be stated in accordance with the existing studies and the review of literature.

After the characteristics of EMM would be understood clearly, the simplification of the geometrical parameters will be made in order to increase the control over the simulation processes. The geometrical behaviour in relation to Customized Spatial Daylight Autonomy (CsDA) which is a measurement tool to calculate comfort, is understood by making various analysis. Following that, the critical orientation, and the climate to be used for the optimization is determined and the research will be taken to a further level by, optimizing the parameters according to the much different cases.

In the end, suggestions about the material limitations and ways of adaptation would be presented to evolve the studies on shading optimization and the usage of expanded metal mesh.

STATE OF THE ART

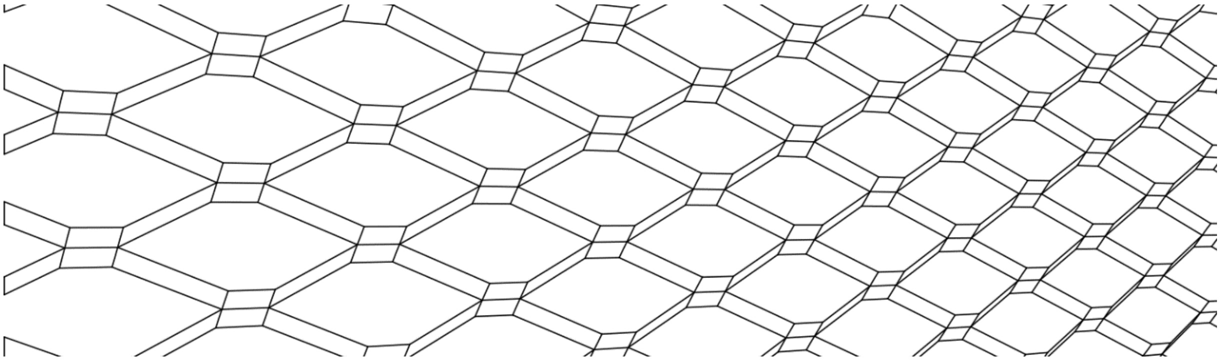


Figure 1: Expanded metal mesh drawing, image credits to the author

1. Architectural State of the Art

The benefits of using expanded metal mesh have led to the significant increase of applications in architecture. High strength to weight ratio, improved shading qualities and appealing aesthetics; are the main reasons for expanded metal mesh (EMM) to be a suitable choice as an envelope component. The studies are showing that; it is possible to increase the energy efficiency up to %30 with an effective application. [3]

Studying the parameters that are changing the behaviour of the material; building an optimized parametric model which adapts to different climates while adjusting to the form of the subjected building, is the focal point of this project. While maintaining the visibility necessities and satisfying the aesthetical concerns, having significant improvements on the indoor comfort, is making it an effective choice for façade applications.

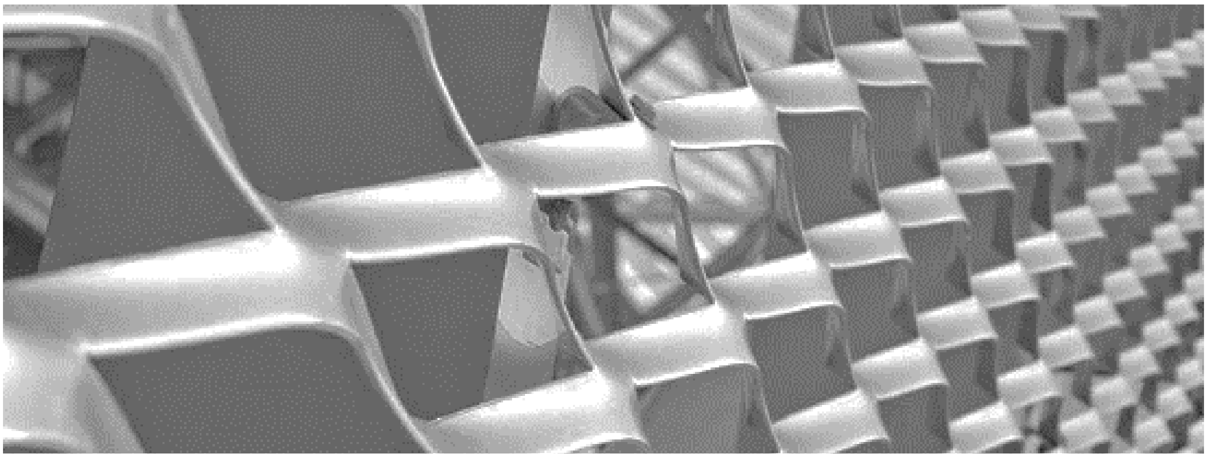


Figure 2: Image of expanded metal mesh, photo credits:https://www.archiexpo.com/prod/james-taylor/product-50366-72728.html

This methodology is aiming to achieve the adaptation of expanded metal meshes to various locations and orientations, enhancing the form that is developed by the architects.

There are many different methods to apply and use this material as an architectural component, because of their ability to be used as shading while maintaining visibility. The most important architectural applications are listed below. [4]

Exterior Cladding: Expanded metal can be curved in both elevation and plan to create a shaped and sculptured structure or add strength and support to exterior cladding used on building facades.

Solar Screening: In many buildings' daylight is welcome as part of an indoor environment, however the heat associated with it is not always welcome nor is the glare and intensity of direct sunlight. For this reason, architects often use expanded metal mesh to provide shelter, when placed on the outside of a glazed building facade. By arranging the size and shape of the diamonds in an expanded metal mesh it is possible to use the strands to deflect direct sunlight and cast shadows on glazing while using the apertures or openings to still provide views and allow diffuse or reflected daylight to enter the building. Further, the pattern can be adjusted as appropriate to address different orientations on different sides of the building such that the level of shading vs. daylighting can be optimized for each side.

Ventilation: In certain cases, ventilation with a semblance of enclosure is needed. This would be the case in structures that do not seek full enclosure such as parking garages or outdoor pavilions for example. Some security and protection are needed but so are ventilation and a sense of openness. Using expanded metal mesh can provide exactly that function on these structures by allowing air to flow freely through the openings in the mesh and even be directed by the angle of the mesh or the shape of the metal strands. [5] Moreover, due to their convenient construction process and production costs, various examples can be perceived in the latest architectural projects:

TECHNO HUB, DUBAI

Figure 3: Techno Hub, Dubai project, Photo credits: https://www.italmesh.com/applications/

The buildings are constituted by a double façade, the outdoor one of which uses the metal sheet mesh as a shading, assembled on a framework. The Metal mesh, framed, keeps the interchange between indoor and outdoor of the building, to control the incidence of sunlight. [6]

Figure 4: Techno Hub, Dubai project, Photo credits: https://www.italmesh.com/applications/

ZERO GRAVITY EDEN, MONTIRONE, ITALY

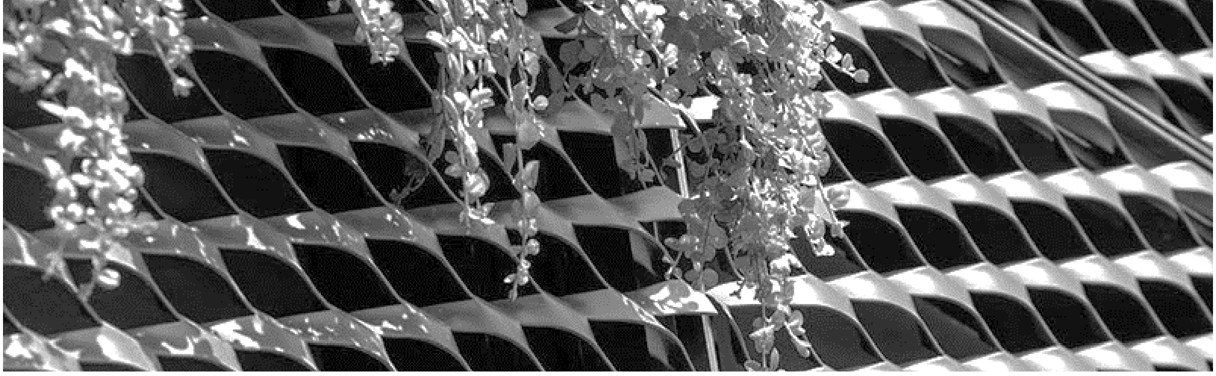


Figure 5: Zero Gravity Eden, Italy, Photo credits: https://www.italmesh.com/applications/

This new green project is supporting the sustainable architecture by its design. With Zero Gravity Eden, the expanded and painted metal meshes are transformed into a wonderful green facade, able to provide thermal and acoustic insulation, as well as a remarkable aesthetic impact. [6]

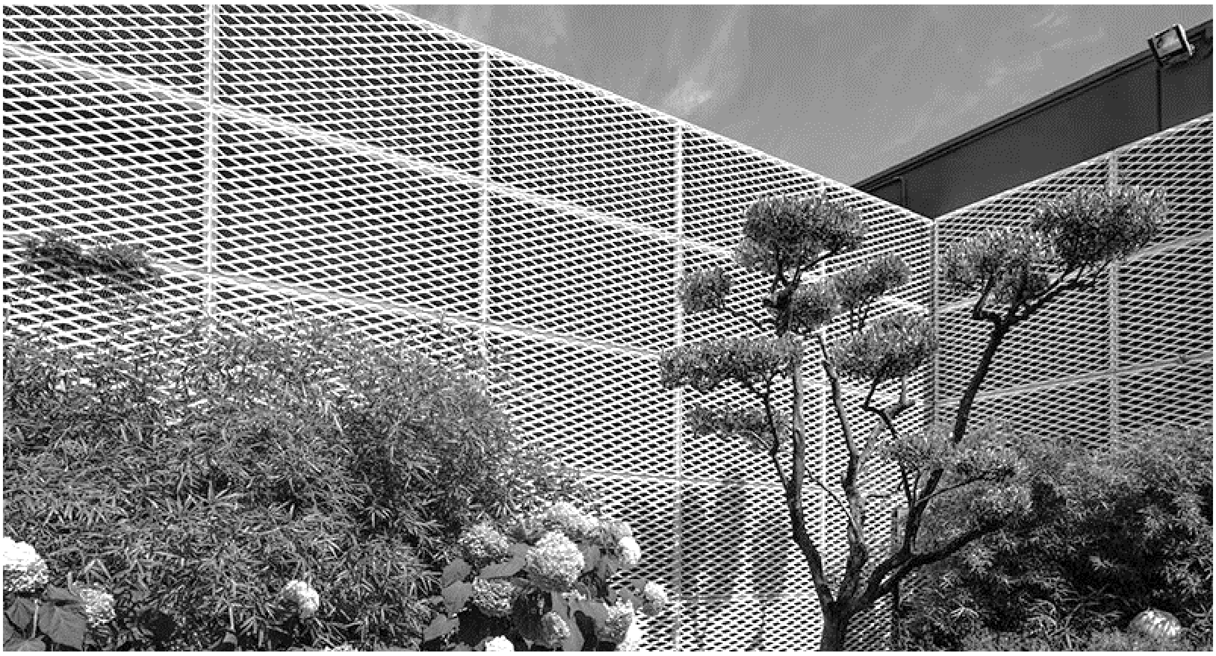


Figure 6: Zero Gravity Eden, Italy, Photo credits: https://www.italmesh.com/applications/

HEADINGLEY CRICKET CLUB

This project design creates a powerful verdant building that blends in well with its surroundings. The pavilion provides accommodation for a mix of uses on five floors for both clients while also respecting daylighting and privacy of the adjacent residential buildings and connecting the green spaces around the pavilion with the locality. On the north and west façade, the rainscreen cladding with its varied perforations, pitches, and tones, visually break down the mass of the building, reflecting the light from a variety of angles. The three-dimensional rainscreen façade is formed from discrete flat panels clad with regular strips of perforated, powder-coated aluminium, supported on a triangular metal subframe, spanning from floor slab to floor slab. It is itself punctuated by an irregular pattern of triangular windows. [7]

Figure 7: Photo credits: https://www.italmesh.com/applications/

MAISON FOLIE DE WAZEMMES, LILLE, FRANCE

The Maison Folie de Wazemmes is an excellent example of how a building facade can breathe new life into an existing structure. By applying modern design principles and benefits to an existing textile factory, this multi-use arts facility enjoys an incredibly eye-catching design that aligns with the facility's overall intent and purpose. The aesthetic benefits are increased through the reflections of light on the steel surface of the EMM, which creates a dynamism on the façade. [8] This benefit is another example of the versatility of mesh facades from a design perspective. Of course, the facade also shields visitors, volunteers, performers, and staff from the harshest effects of sunlight entering the building during the day as well. This example of an expanded metal mesh demonstrates how a wide range of buildings, both old and new, can create a distinct atmosphere with the carefully designed and applied façade. [7]

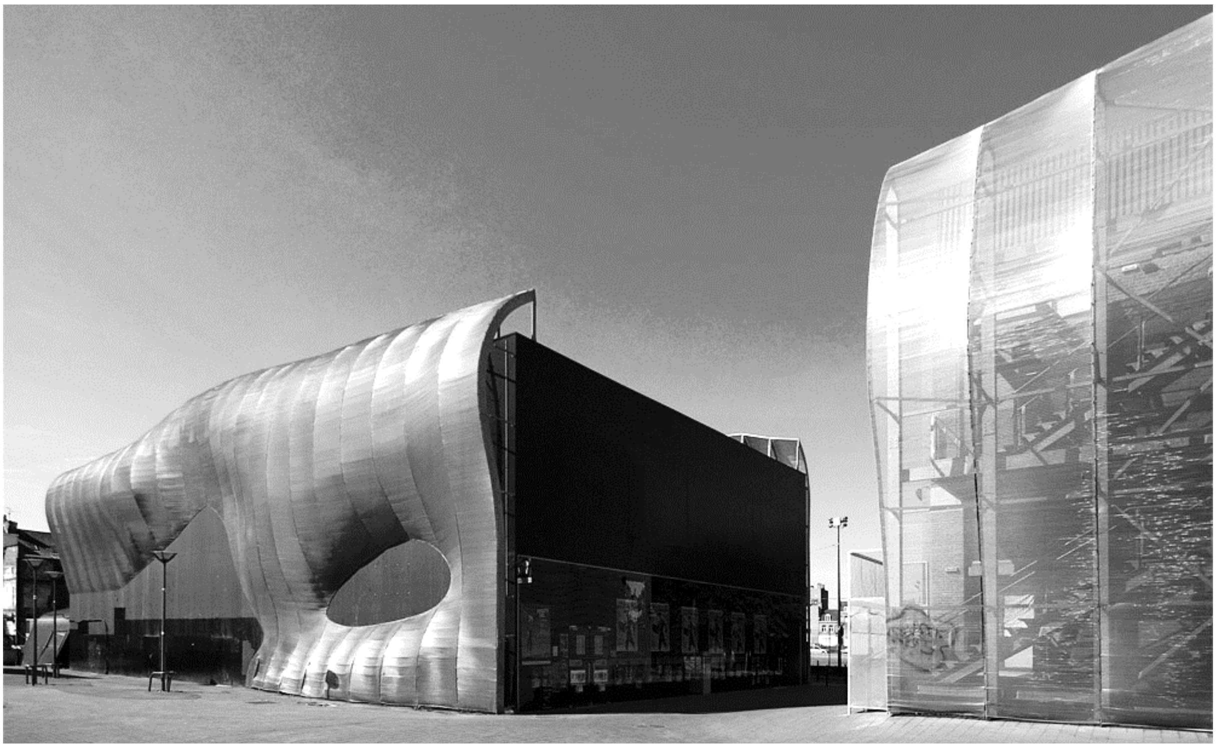


Figure 8: Maison Folie de Wasemmez, https://www.italmesh.com/applications/

THE CONCEPTUAL APPROACH: The part of the program that requires a new building is both a very technical but also a very introverted program: basically, it is best served by an assemblage of boxes that shut themselves off the city but fit exactly within the urban scheme of the Wazemmes neighbourhood. Especially since Wazemmes is such a damaged area, the architects have decided to finish the street with a façade. A black box that glows externally with a luminous skin is designed which transforms with movement in and around the Maison Folie. This glowing, almost holographic dress incorporates all the pulsations of art and life. The articulation of the façade is generated through a continuous variation and modulation of the vertical tectonics of the façade of the old factory: bending vertical lines in a complex pattern that produce a whole range of effects when walking or driving by, enhanced by the position of the sun. This interesting idea have come into life by the usage of expanded metal mesh that is providing the façade with all the necessary properties. The social exchanges, the interaction between programmatic elements is stimulated by an architecture of continuity, an uninterrupted connective surface. Connecting hammam to children's playground, to brasserie, to art school, to exposition, to party room, to the home of the artist, to the salle de spectacle, to the inhabitants of the neighbourhood. [9]

Figure 9: Maison Folie de Wasemmez Images, Photo Credits: https://www.archiweb.cz/en/b/maison-folie-de-wazemmes

The building has many different functions as mentioned before, however the most significant can be considered as studio/ exhibition. That is why a space having this function is selected that has the expanded metal mesh on its façade. The building is modelled as the first step of the analysis process within the information that are given below. All the components are introduced to grasshopper to be used for the adaptation process as well as the daylight comfort simulations. [9]

Figure 10: Maison Folie de Wasemmez, https://www.italmesh.com/applications/

ALI MOHAMMED T. AL-GHANIM CLINIC, KUWAIT

The facade of the Ali Mohammed T. Al-Ghanim Clinic in Kuwait is another instance of facades combining practical and visual benefits. The overall building design places its courtyards and similar interior spaces within the facade, which plays a critical role in filtering and deflecting light. In a consistently hot, dry climate, offering access to outdoor spaces while reducing potential issues like heat exposure is critical. This expanded metal mesh facade also makes an incredible first impression. While not a traditional design for a healthcare building, it is both memorable and easily distinguished from a distance. The ease with which visitors and locals can identify the structure is a significant advantage in terms of branding and recognition. [6]

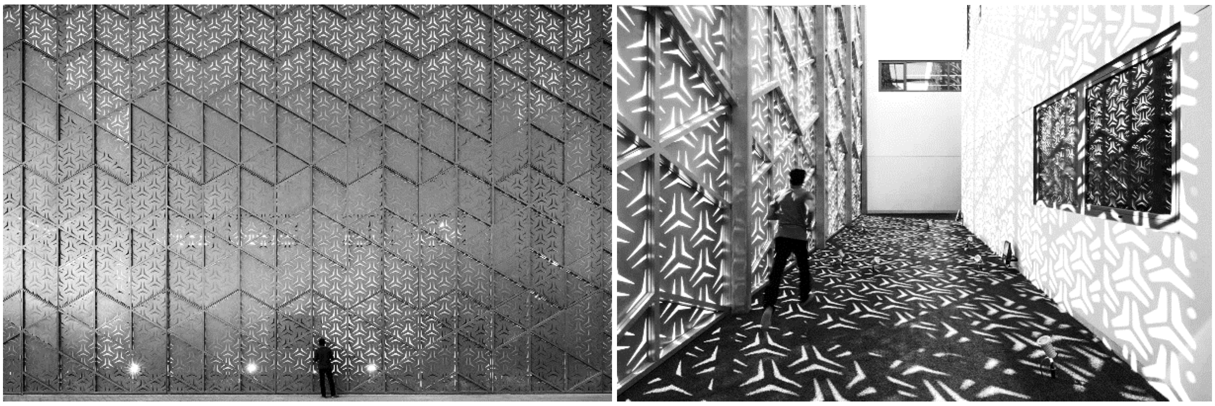


Figure 11: Ali Mohammed Clinic images, Photo Credits: https://www.italmesh.com/applications/

THE PREMONT LANTERN, QUEBEC

The building is located where La Capital express way crosses Pierre-Bertrand Boulevard, in an environment marked by the type of generic architecture found in city outskirts. Access to the sector was designed with cars in mind, and buildings are laid out on rigid, regular, anonymous plots of land. Many of the buildings dotting the countryside were built with small budgets. Their design is banal and minimal, with no thought for the place in which they were built. This accumulation of metal boxes creates a repetitive landscape that meets an immediate need but has no long-term vision. In this context, the Prémont Harley-Davidson building achieves distinction by having its own identity and a design appropriate to the site and its characteristics. [10]

Figure 12: The Premont Lantern, Photo Credits: https://www.archdaily.com/355636/the-premont-lantern-bourgeois-lechasseur-architectes

Although most of the buildings in this sector sit solidly on their lots, the Prémont Harley-Davidson building opens out in a band that turns back on itself in a "U" shape; thereby turning its back to the highway to create a protected yard on the other side. This space, a sort of microclimate, gives the building's surroundings a more human scale and provides protection from noise, wind, and pollution. On the side nearest the boulevard, a large green band runs the long of the building and contrasts with the surrounding paved surfaces. The parking area is towards the back and parallel with the building. This allows the showroom to be in front on the boulevard.

Depending on the time of day, one of the building's highlights is its double skin of black aluminium that acts like a theatrical veil, creating a cut-out on the main building by day and shining by its absence at night. From the highway, the grill lends movement to the façade thanks to the moiré effect when cars travel quickly by it. The layers that make up the envelope give the effect of depth, opaqueness, and light to pedestrians walking by. The metal skin is made in such a way that it gradually reveals the interior. During the day, the metal grill gives the impression of opaqueness and creates a play of shadows. This material brings to mind the metal used in the neighbouring industrial buildings. At night, the skin filters the light that comes from inside and transforms the building into an immense lantern. Perforated with large openings, the veil allows light to be filtered inside and creates a play of varying shadows. [11]

One of the more interesting aspects of the design is its double skin of black aluminium. The layers making up the façade give it depth and the sense of movement as vehicles travel by it, while also helping to filter light, providing different effects at both day and night. The metal grill gives the impression of opaqueness and creates a play of shadows as it gradually reveals the interior through the use of large openings.

As visitors approach the building, the envelope frames a two-story high opening that displays a few motorcycles and sets the tone of the rest of the visit. Measuring around 8000 square meters, the building contains a large showroom situated in front on the boulevard, a museum that includes several collectors' items, a large repair shop, a theme restaurant, and administrative offices.

The usage of the expanded metal sheet in the façade of the building is not only for the purpose of daylight control but also aesthetical reasons. That is why it is not used throughout the whole façade. There are some parts that are cutted out. That is why, for the selection of the simulation space, one that has both expanded metal mesh and unshaded glazing in front of it is considered. Below, the visualization of the model of the selected space as well as the location of it with regard to the whole building is represented. [10]

BBVA COMPASS STADIUM, HOUSTON

BBVA Compass Stadium is designed to be the core of Houston's East Downtown Redevelopment Plan. With a 22,000-seat capacity, its primary use is as a soccer stadium. However, it can also accommodate lacrosse, rugby, or concerts. To create something specifically as an architectural icon is a challenge in itself; Populous additionally had to design the stadium within the constraints of an extremely tight construction budget of $60M. [12]

For the design of the stadium, the team of architects and engineers used building-information modelling (BIM) to enable a highly collaborative effort, from schematic design through construction documentation. By working with one main model, updated weekly, the involved parties could get the stadium into construction quickly and have it finished in just 14 months—a boost for the team and its fans, who had been waiting through five years of city negotiations.

Figure 13: BBVA Compass Stadium, Photo credits: https://www.archdaily.com/427206/bbva-compass-stadium-populous

THE CONCEPTUAL APPROACH: Bright orange now appears on seats and signage, as well as on polycarbonate-sheathed walls beneath the signature metal-mesh facade. Clad with 94,000 square feet of anodized-aluminium panels, which were machine-expanded to create a tessellated pattern, the steel armature is lit from below to turn the stadium into a glowing, circular urban beacon.

If Herzog & de Neuron's 2008 Beijing National Stadium (aka the Bird's Nest) comes to mind, Spear offers a certain rationale: "*We wanted the structure to reflect both the musculature of the players and the industrial history of the area*."

The apparent random shape of the building represents an efficient choreography, says Bart Miller of Walter P. Moore, the structural engineer for the project. Triangles form the facets of the skin, and the corners function as connecting nodes—so that every steel connection is exactly the same. The mesh allows air to flow freely through the stadium, but since it had to withstand hurricane-strength winds, the engineers gave the fabricators a deflection limit for load-testing different materials at various thicknesses. [13]

The concept itself was the main reason why this building has chosen to be analysed. The expanded metal mesh has been applied on the triangulated surface in such a clever way that, it enhances the design ideas by its filtering view but at the same time by its performance qualities where it provides natural ventilation and daylight control. Moreover, the space it creates in between the cladding and the glazing due to the three-dimensional triangles makes it interesting to compare with the other case study building which have significantly different surface qualities. [14]

CONTEMPORARY ART MUSEUM, NEW YORK

The New Museum of Contemporary Art, designed by Tokyo-based architects Kazuyo Sejima and Ryue Nishizawa/SANAA with Gensler, New York, serving as Executive Architect, is an eight-story, structure located at 235 Bowery between Stanton and Rivington Streets, at the origin of Prince Street in New York City. The first fine art museum ever constructed from the ground up in downtown Manhattan, the New Museum has opened to the public on December 1, 2007, coinciding with the institution's 30th anniversary. [7] "*It was complicated to organize the architecture around all of the desires*," Sejima and Nishizawa have said. "*We knew we could not maximize the entire site with solid architecture, we had to reduce the building's mass somehow to create space between it and the perimeter. The solution of the shifted boxes arrived quickly and intuitively. Then through trial and error we arrived at the final, ideal configuration. Now we have a building that meets the city, allows natural light inside, gives the Museum column free galleries and programmatic flexibility, and expresses the program and people inside to the world of New York outside*." [15]

Figure 14: New York Contemporary Museum of Arts, Photo Credits: https://www.archdaily.com/70822/new-art-museum-sanaa

The location context, Lower Manhattan, with its squared blocks and buildings, can be considered as starting point for the Museum image: it replies the boxes surrounding, and stacks them one on top of the other in various sizes and heights, as the plot was a playground for a composition of cubes. By small but significant shifting of the cubes, the building gets dynamicity and an attracting shape, being different but similar to the near constructions. The program of the Museum consists of four public galleries at the first four floors, which have free and flexible spaces for exhibitions; a "white box" auditorium in the basement, Education Centre at the 5th floor, offices at 6th, a multi-purpose room at the 7th. By shifting the boxes, all galleries get natural illumination, combined with artificial, and the offices and the private locals on the top floors get terraces and opening views to the cityscape. [16]

Figure 15: New York Contemporary Museum of Arts, Photo Credits: https://www.archdaily.com/70822/new-art-museum-sanaa

Figure 16: New York Contemporary Museum of Art, façade cladding images, Photo credits:https://en.wikiarquitectura.com/building/new-museum-of-contemporary-art-in-new-york/#

Evidently, at night the Museum shows life from the inside with the artificial lights through the hidden openings, enhancing the gaps between the volumes and giving more lightness to the massive building.

The facade is covered with a mesh-shaped aluminium honeycomb designed by architects to highlight the volumes of boxes and at the same time put on the building. These silver anodized aluminium panels and tear in areas open windows or skylights, allowing its opening to the environment and the accentuation of the volumes of the "boxes". Visitors can see out of the building through this network shaped aluminium honeycomb, which had never been used to coat the facade of a large building. [15]

THE YOUNG VIC THEATER, LONDON, ENGLAND

The Young Vic is a famous producing theatre in south London, originally designed in 1970 as an informal, temporary space for the National Theatre company. Thirty years later, the theatre had become one of Europe's most important producing houses but the building itself had become physically dilapidated, too small, too energy hungry and technically obsolete. [17]

Because the innovative thrust stage auditorium had proved a potent performance space and the old butchers shop foyer an important vessel of communal memory, the rebuilding project re-imagined a new theatre grown around these two fragments, upgrading the auditorium for even greater theatrical flexibility and adding an enlarged foyer bar, two new studio theatres and much improved support spaces.

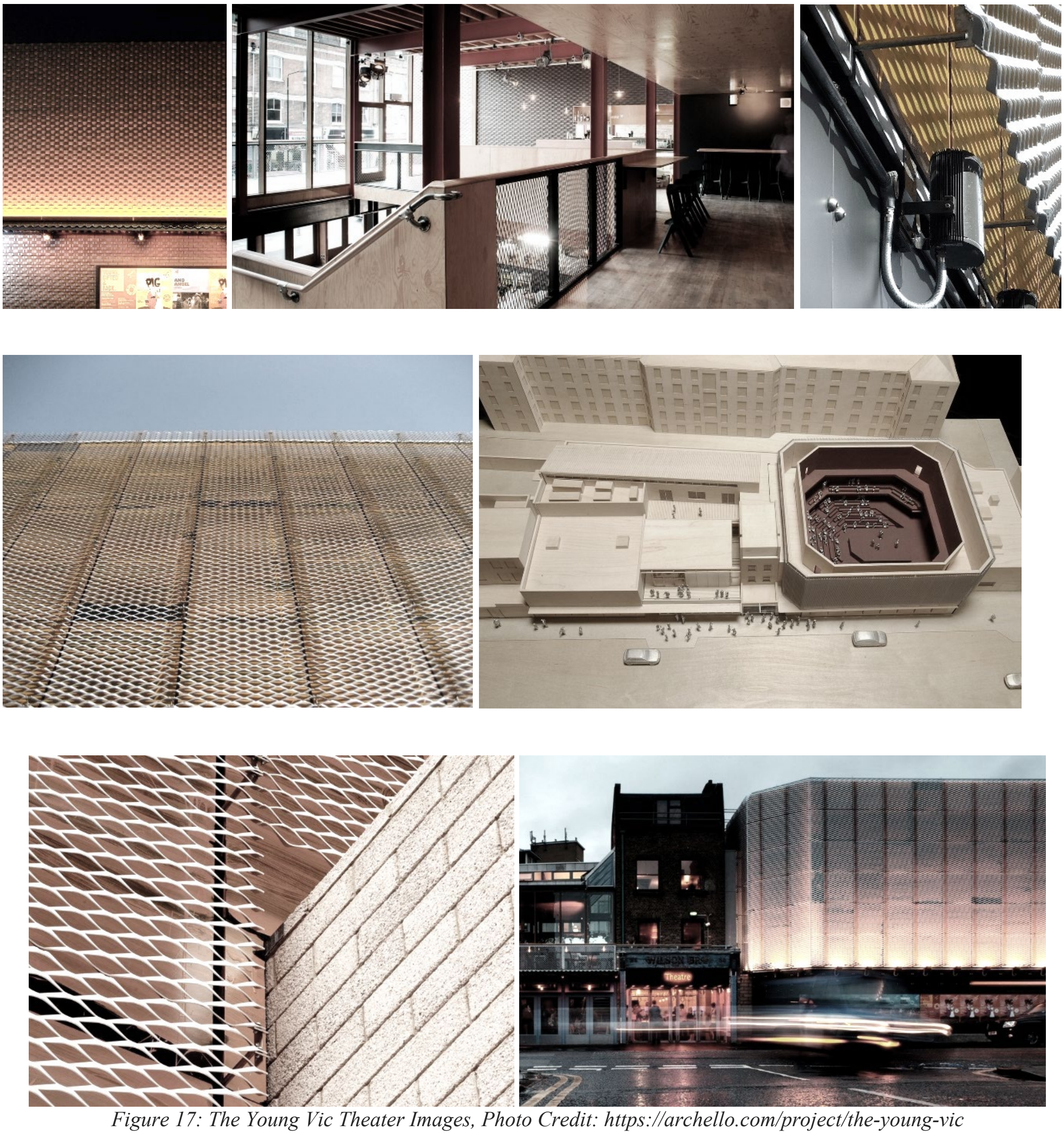


Figure 17: The Young Vic Theater Images, Photo Credit: https://archello.com/project/the-young-vic

At the heart of the new building is a multi-functional bar and foyer space, conceived as a natural extension of the public street, connecting directly with all three auditoria and serving as a public living room for the local community throughout the day and evening. There is no separate stage door - actors, staff and public enter and leave the theatre together.

Artist Clem Crosby painted a series of monochrome panels for the new auditorium façade, layered with aluminium mesh and up lit to create a theatrical gauze effect. The unique, hand painted auditorium signifies the live, unrepeatable nature of the theatre events happening within. The larger studio theatre is clad in geometric brickwork to reference the diagonal mesh of the main house. The building is designed along passive low energy principles, combining high insulation levels, natural ventilation, shading and orientation to reduce the building's carbon footprint. The 'public' and 'private' territories of the theatre as a whole are deliberately merged to heighten the sense of a shared democratic architecture. [17]

Transformation and provisionally were the key theatrical ideas on which the design was founded. The project was conceived as a connected group of distinct elements. An early decision was taken to retain the butcher's shop, which is both a symbol of the Young Vic, and has strong local resonance as the only survivor of a direct wartime bomb hit on The Cut. The existing auditorium was given a skin of hand-painted cement board panels by artist Clem Crosby (the exterior of the auditorium is the largest externally displayed studio painting in the world). Silver mesh in front of them is up lit at night to emphasize the transformation from working daytime to celebratory night-time modes. The large new studio theatre was texturally related to the auditorium by the use of a similarly scaled 'weave' of dark, profiled brick. The public foyer was expressed as a lightweight timber and steel structure in the 'courtyard' between the principal performance studio and the butchers' shop. [17]

2. *Technological State of the Art*

The material used in this research is the main technology that is investigated and examined. Expanded metal mesh is considered to be one of the "greenest" materials on the constructions market. No scrap is generated in the production process even though it is punched, slit, and stretched in one motion. A typical expanded expand the raw material more than 300%; it varies depending on the product. The production has a low environmental (zero waste) impact which also translated to a lower overall cost. [18]

The case and projects that are studied are showing that: "Use of expanded metal as a sunshade or a building envelope can greatly reduce interior cooling cost, while maintaining beneficial solar gain for heating cost reduction**."** [19] Using expanded and perforated metals helps attain recycled materials credits. Material and Resource (MR) credits are available for construction waste management, recycled content and use of regional materials. Energy and Atmosphere (EA) credits using architectural meshes for shading on interior sections and exterior facades of building design can help to reduce solar effect and energy required to run HVAC systems. [18]

While one of the trendiest materials in the market is being analysed, the methodology to do so, gains much importance. Parametric design has become one of the leading topics in the world of building and architectural engineering, due to the developments offered in terms of sustainability by managing building components with respect to daylight and energy analyses.

Using the program “Grasshopper” with plug-ins “Honeybee (version 0.0.65) and Ladybug (version 0.0.68)” [2]; this project is aiming to build an adaptive model of a shading system with expanded metal sheets. The adaptation is within the limitations of materials’ geometrical parameters which are changing according to the sun path, indoor visual comfort, incident radiation and the desired illuminance levels inside a defined space, that can be located in any of the climate zones. Moreover, the improving methodologies to produce expanded metal sheet is allowing the application to be made in surfaces with various geometrical properties, also supported by parametric design.

Our approach to assess the performance of our shading system made with expanded metal would be with Grasshopper. The aim is to build a script which allows the parameters to change along with the obtained results given by Ladybug and Honeybee. Since there are various types of results which can be given, it is important to choose the most strategic ones.

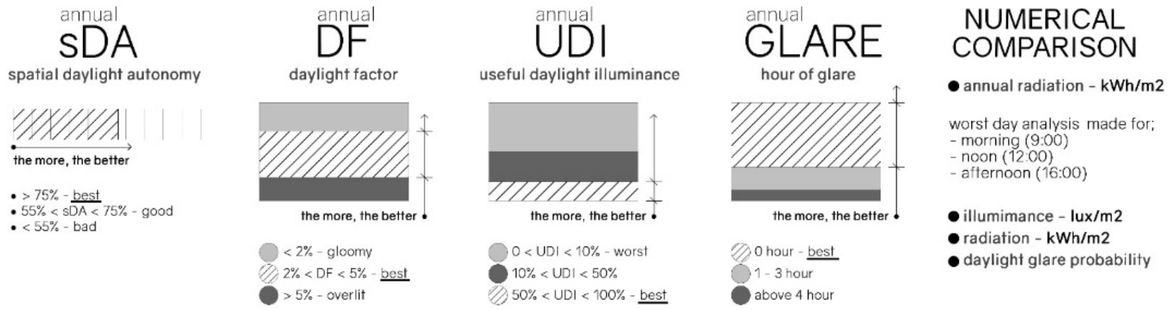


Figure 18: Daylight/Energy Simulation Measurements, Photo credit belong to author

Commenting and understanding the results also requires a strategic methodology since the impact and the behaviour can be assessed by comparison. The common tools are offering many evaluation outputs, some of them being listed above, that are usually aiming to indicate the daylight levels inside with respect to the defined indoor comfort levels. While the coherence of the outputs is very important to make a comparative analysis, the detailed analysis testing as many assessment methods as possible, would make the process reach to a more accurate and realistic level.

This research is exploiting the advantages of grasshopper and its components in terms of this matter by using Honeybee to calculate and simulate the indoor comfort in terms of Customized Spatial Daylight Autonomy as well as optimizing the values by using Octopus.

3. Technical State of the Art

The significance of the work that this research is doing can be stated as; by studying the parameters that are changing the impact of the material, building an optimized parametric model which adapts to different climates and surfaces; is the focal point of this project. While maintaining the visibility necessities and satisfying the aesthetical concerns, having significant improvements on the indoor comfort, is making it an effective choice for architectural façade applications. This methodology is aiming to achieve the adaptation of expanded metal sheets to various locations and orientations, without having any geometrical limitations, supporting the aesthetical decisions of the designers.

Since the shading devices blocks solar radiation, it also reduces the daylighting in the building, so artificial lighting is required to achieve comfortable illumination, thus resulting in more energy consumption. For this reason, whether the shading device can effectively reduce the total energy consumption of a building, is worthy of discussion.

[20] The case study in another research related with the EMM were using a typical medium-sized office building with a 40 m x 40 m 10-story RC structure. WWR at 30%, 50%, and 80% and three kinds of glazing, laminated clear glass, laminated blue glass, and Low-E glass were examined. In the study, the daylight standard of Leadership in Energy and Environmental Design (LEED) was used for evaluation. Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) were adopted as two important measures for better understanding annual daylight availability and quality, as well as glare potential.

The results showed that the expanded metal mesh effectively reduced direct and excessive sunlight. Nevertheless, if a Low-E glass with a low visible transmittance was used, the influence of the expanded metal mesh on preventing excessive light was also lowered.

The energy saving ratio of the scenario with 80% WWR was greater than the scenarios with 30% and 50% WWR, meaning that the greater the WWR, the greater the energy saving potential of expanded metal mesh and glazing. As for glazing type, the lower the SHGC value of the glass, the smaller the influence of the expanded metal mesh on HVAC energy saving. [21]

To save air conditioning energy consumption, expanded metal mesh with a low perforation rate was used, which then increased lighting energy consumption due to insufficient illumination. When Low-E glass with a low solar heat gain coefficient was used, the expanded metal mesh resulted in a significant increase in lighting energy consumption.

In conclusion, the results demonstrated that the expanded metal mesh could effectively reduce direct and excessive sunlight. It was also shown that WWR is the main factor influencing the amount of daylight entering the building; therefore, the greater the WWR, the greater the energy saving potential expanded metal mesh and glazing have.

The study made in this research is indicating the importance of geometry, using an outdoor comfort model based on radiation exposure and wind velocity. An interesting example located in Hong Kong that is controlling the illuminance levels inside by façade reflectors.

It is also stated the parametric approach for these daylight and energy aspects should be used more on the practice level, also by responsive geometrical design solutions. A balanced solution for to provide both visual comfort and adequate daylight levels in order to reduce energy consumption is a highly difficult task.

[4] Another research is focused on, integrated analysis of daylighting and energy consumption of spaces with Perforated Solar Screens, through controlling its perforation percentage, matrix, and shape, by using the orthogonal arrays (DOA) statistical method gave the results of; %50 increase in daylit area, %55 reduction in the total energy demand. Due to its efficient results, PSS became very popular with the shift from traditional to modern architecture. However, having many domains that interact in many levels, makes it very complicated to analyse. In order to understand how, daylight performance of a building model is assessed; it is crucial to understand how the methodology and the software have come to life. Previous studies have demonstrated the significant steps of the history of simulation tools. [22]

Energy Plus utilizes the **split flux** method to model the interior reflections of light by dividing the luminous flux into two components; then, each split component is reflected by an average weighted reflectance of the surfaces above and below the window, not that accurate. [23]

Lagios, Niemasz and Reinhart [24] linked Rhinoceros/Grasshopper to **Radiance/Daysim** in order to evaluate key design parameters. **Azadeh** [25] proposed a process for utilising daylighting and energy analysis software for optimising the performance of a sun-shading screen. To further understand the available daylight in the test space, a climate-based metric was calculated in DIVA. In order to model the effect of the screen on the energy consumption, the screen's hourly shading coefficient was calculated. An electric lighting schedule for the year was then generated and loaded into Design Builder for thermal simulations.

González and Fiorito [26] integrated parametric design with performance simulation tools. They used Galapagos/Grasshopper to define randomly the set of tests and then used DIVA both to calculate daylight metrics and to create an artificial lighting schedule. Finally, they used the DIVA thermal component to calculate the energy consumption and CO_2 emissions. **Trubiano** [27] integrated the use of Grasshopper with Radiance and EnergyPlus through Matlab. Adopting genetic algorithms and a single objective function, they developed an evolutionary optimisation script to demonstrate the possibility of generating the optimal shape of atriums. **Lobaccaro** [28] applied a similar method for optimising the geometry of a building in order to maximise the envelope’s annual exposure to solar radiation. **David** [29] applied the combination of daylight and thermal analysis for assessing solar shade efficiency. In order to rate the performance of different typologies of external overhangs, they used Radiance and EnergyPlus to calculate the shading coefficient, cooling energy demand, daylight autonomy, sun patch index and useful daylight illuminance.

DAYSIM is a Radiance-based daylighting software that employs a reverse raytracing algorithm based on the physical behaviour of light in a volumetric, three-dimensional model. It employs Daylight Coefficients method and Perez All-weather sky model to calculate the annual number of illuminances and irradiances in and around buildings. **Radiance** is a validated backward ray tracer capable of simulating complex geometries with flexible reflection and transmittance material properties. Its scientific reputation is further founded on a series of independent validation studies, which have demonstrated that Radiance is capable of modelling interior illuminances and irradiances for a wide range of sky conditions, a wide range of diffuse and specular reflecting real world materials, standard glazing and complex façade geometries. [4]

[31] Sensor point, ranges thresholds and locations should be determined strategically for the simulations. The parameters should be describing lighting system for each different zone, target illuminance, the lighting power density, lighting control system. The results that they obtained in order to compare variations are:

- **Annual solar irradiation** profile is calculated with DIVA. (vertical plane)
- Hourly shading profile
- Hourly transparency schedule
- **Annual energy calculation** (input loads are determined for thermal dynamic simulation) + (define the thermal behaviour, how the solar radiation is distributed)
- Balancing daylighting and thermal performance

Over the past decade, the architecture industry has experimented with many metrics for measuring daylighting. Daylight Factor was a common metric before, however, has fallen out of favor because it is entirely independent of location, climate, and building orientation, and has proven a poor predictor of actual performance. Point-in-time measures (e.g. illuminance on September 21st at 3:00 pm) can be useful for understanding best- or worst-case scenarios, but do not give a good picture of whether a space or building is performing well overall. [32]

In recent years, the profession has moved toward dynamic daylighting metrics, which are location-based while using actual weather data, similar to energy modeling tools and annualized (i.e. they summarize performance over the entire year). The USGBC codified two of these metrics in LEED v4: Spatial Daylight Autonomy (sDA) and Annual Sun Exposure (ASE) — metrics that together paint a clear picture of daylight performance and more importantly can help architects make better decisions for daylighting design. [33]

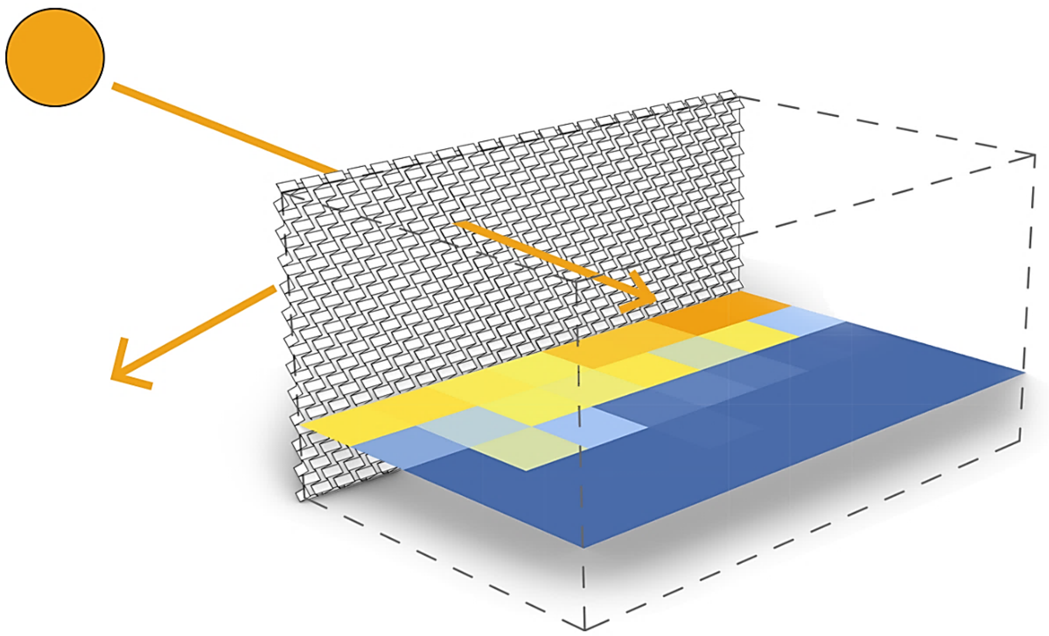


Figure 19: Diagram about the Honeybee Daylight Simulations, credit belong to the author

In 2000, the U.S. Green Building Council (USGBC) introduced the LEED rating system to standardize metrics for several primary sustainable design characteristics, including daylight. But equitable comparisons of daylight performance still weren't possible until 2013, when the Illuminating Engineering Society (IES) adopted and published the testing and calculation guide Lighting Measurement 83 (LM-83), Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE).

LM-83 is the first IES-adopted, evidence-based annual daylighting performance metric in the lighting industry. It resulted from a six-year-long research effort by the IES Daylight Metrics Committee (DMC), led by the energy-efficiency consultant Heschong Mahone Group (now a part of the TRC Companies), that included human-factors field research in which subjects answered questions about their visual preferences and comfort levels in more than 60 spaces across three building types (classrooms, offices, and other) and several climate zones. The DMC, an international team of about 15 daylighting experts, building scientists, designers, manufacturers, and code consultants, also fostered the development of computational methods to run annual daylight simulations of the same spaces studied in the field, vetted the results, and crafted the resulting daylighting guidelines and criteria within LM-83. [33]

3.1. Material Overview

[34] *Expanded metal mesh which can be used for exterior facade is a form of metal sheet with various shaped openings in the area. There are two distinct varieties of expanded metal mesh: standard and flattened. The term "standard expanded metal" refers to the metal as it comes out of the expanding machine. On the other hand, flattened expanded metal is what happens when standard expanded metal is put through a cold rolling steel mill to flatten the expanded metal mesh out.*

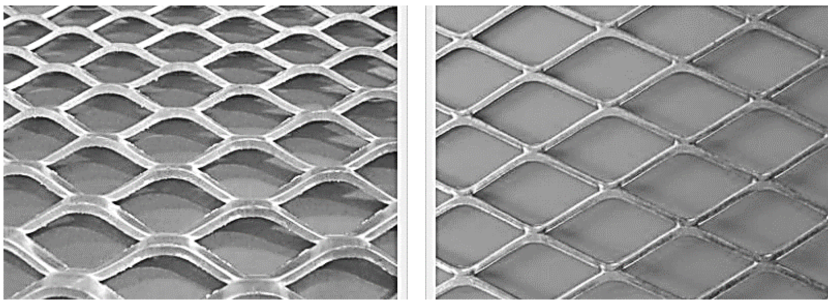


Figure 20: Expanded Metal Mesh images, Photo credits: DIRECT METALS, product catalogue

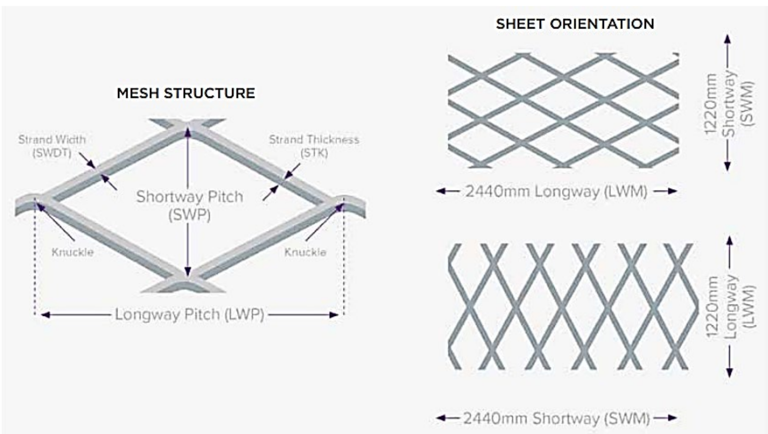


Figure 21: Expanded Metal Mesh Geometry Explanation, Photo credits: https://www.expandedmetalsheet.com/expandedmetal/specifications.html

The key design trait of expanded metal mesh is its versatility. The technical and manufacturing aspects of the product allow for custom fabrications but without a custom price tag. Hence it is enjoying a variety of uses in buildings. The light weight and strength of expanded metal make it an ideal material for a wide variety of commercial and industrial security applications; in addition to these, there are a growing number of applications where the use of expanded metal mesh is making a design statement and enhancing the overall building design.

PROPERTIES: The metal mesh has a high strength to weight ratio. The products retain the lightweight credentials with the metal sheet that make the metal mesh a simple to install choice. Expanded metal is an ideal material for use on building exteriors due to the fact that it is available in a range of durable and long-lasting choices and therefore can withstand the rigor of exposure to weather, wind, and other environmental factors. Another important property is anti-corrosive and for this reason it is a durable material.

APPLICATION: It can be used in a variety of different ways:

Exterior Cladding: The ability of expanded metal mesh to be visually appealing as a building façade material as well as being an effective element for the wall assembly makes it a popular material in the market for the architects. It has many different advantages in use, including the fact that it can be adapted to various surface geometries while adding strength and support to the building façade. That is why, it is highly used as an exterior cladding in the architectural world.

Solar Screening: Daylight control is an important aspect of the design due to the aim of increasing visual and thermal comfort inside the spaces. However, the problem of glare and excessive heat should be avoided to provide comfort. Expanded metal mesh, gives the possibility to the architects to use it as a barrier between the outside and inside, applied on the glazed building façade. The geometrical characteristic of it provides an efficient control of daylight, specific to the conditions of the building, by the use of strands that deflects direct sunlight and cast shadows on the glazing. Moreover, the main advantage of this usage is that, while these comfort aspects are provided, the visual comfort is still maintained thanks to the holes. The geometrical properties of it can be exploited within the variations of the dimensions, depending on the buildings' requirements.

Ventilation: Expanded metal mesh can also be used for ventilation purposed thanks to its holes that are providing a sense of openness, by allowing the air to flow freely through the openings in the mesh. Depending on the function of the structure, the EMM can be implemented in many different ways to both provide and enclosure and allow the air flow.

SURFACE TREATMENTS: Because of its adaptability to metal finishing processes, **expanded metal can be galvanized, anodized, coated, painted, or plated for a variety of applications**. Because of the light lubricant used during the expanding process, the product should be cleaned prior to finishing. Some of the lubricant used in manufacture is usually present on unfinished expanded metal surfaces and aids in the prevention of corrosion. When requested to furnish the product dry, the supplier shall not be responsible for conditions resulting from the absence of lubricants. In hot-dip galvanizing, there can be some warpage of metal because of high temperatures. In addition, galvanizing does not always produce a smooth and even coating. It is recommended that patterns of

12.7mm, lighter than 2mm, and large diamond patterns with a light weight per square foot not be galvanized. Consideration should be given to producing these items from pre-galvanized sheet metal. [34]

MATERIALS: The expanded metal mesh can be made of a large range of different materials including, carbon steel, aluminium metal, stainless steel metal and nickel metal. However, the aluminium EMM is used the most commonly due to its light weight and the resistance to corrosion. Moreover, the production of it which is by expanding the metal surface by a machine, makes it stronger, lighter, and rigid that gives its advantage to be used as a self-supporting building façade component.

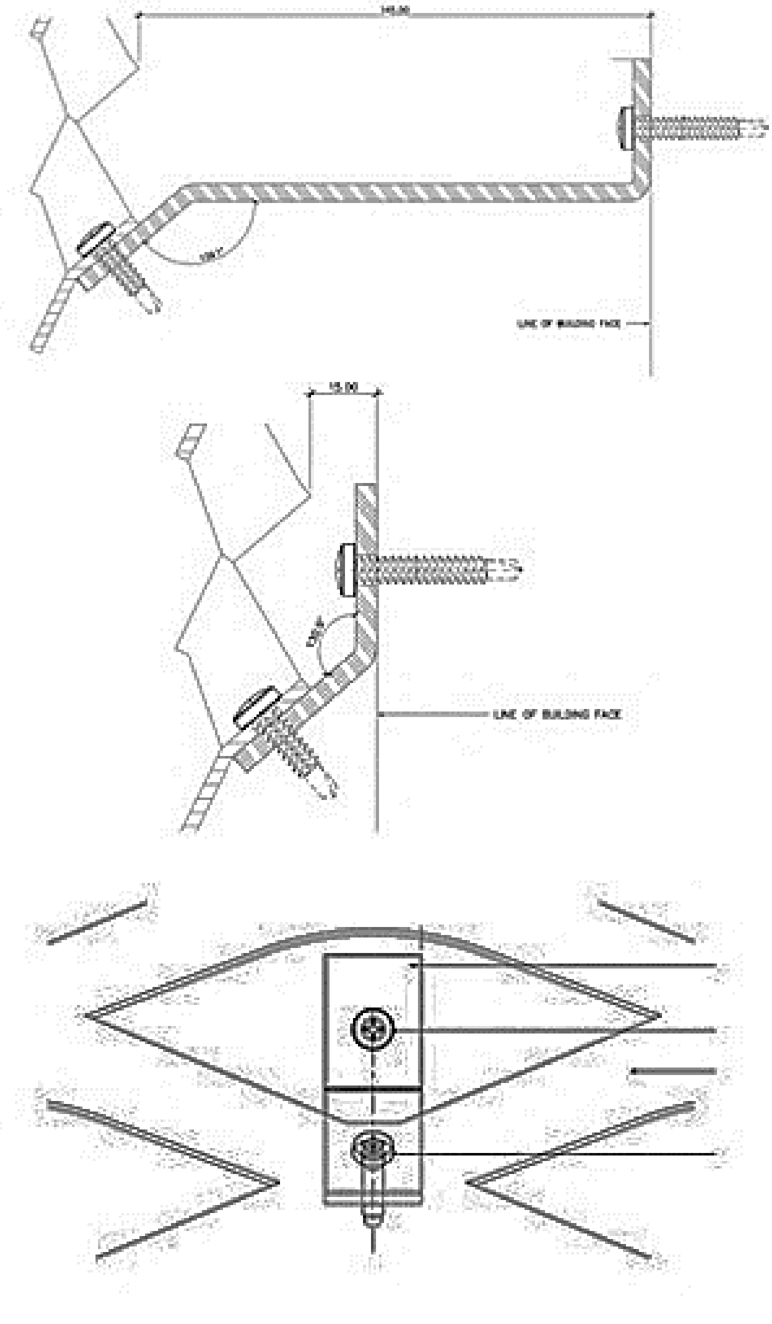


Figure 22: Expanded Metal Mesh Application Details, Photo credits: https://continuingeducation.bnpmedia.com/courses/areditorial/expanded-metal-mesh-in-architecture/6/

PIECE AND COIL SIZE: The sheet size of the expanded metal mesh is the consideration to be made after the design of the pattern and style of the expanded metal mesh is determined. The most convenient way of choosing it would be to use the standard measurements that are provided by the manufacturers to save from time and cost. Moreover, for the specific cases, most of the manufacture companies provide customized dimensions specific to each design; if the quantity of the request is sufficient. The design of the edge of the mesh, is also an important consideration to be made for the production of the EMM. It can be cut, sheared or randomly crossed through the solid and open parts of the mesh. All these aspects must be correlated with the size of the sheet and the size of the patterns, meaning that there is a certain proportion required for the production to be possible. That is why, it is recommended to work with a consulting manufacturer, to be able to make the effective decisions about the production limitations.

In general, because of the additional operations involved, sheared to size expanded metal will cost more than stock size sheets or machine run closed diamonds. Shearing allows for tighter tolerances but will create open diamonds on any edge that is being sheared. Special size sheets can be furnished provided the sheet dimensions represent even multiples of the dimensions (both LWD and SWD) of the diamond pattern specified and provided that normal manufacturing tolerances will be acceptable. Stock-size sheets of most catalogued expanded metal products are generally available in quantity from steel distributors or from manufacturers. Practically any special design, size or shape can be produced to customer specification. Some patterns are available in coil as well as flat sheets. Custom manufactured sheet sizes or pieces, or material in coil form, are generally available on special order. [34]

SHIPPING AND INSTALLATION: One of the other advantages of the expanded metal mesh is that it can be used as a prefabricated material, where the panels are produced in the factory and brought to the site, ready for the installations. Depending on the requirements the mesh can be shipped both in coil and panel size.

The installation can be made in different ways depending on the design. It can be installed into the frames or can be attached to the building façade with the necessary connection details. Manufacturers are also providing way of installation that the connection of it would not break the visual appeal of the mesh by using mesh fastening clips. These clips provide the various separation methods from the supporting structure by their differences in the size and shape. The manufacturer companies provide specific solution to each design and develop efficient connection details when different solutions are needed. These procedures should be indicated through the drawings and the specifications of the project. The last point of the installation process to be highlighted is the cleaning and the maintenance aspects, where all the requirement should be stated, and the regular controls must be made within the defined time ranges. Below the production process is explained with a simplified scheme.

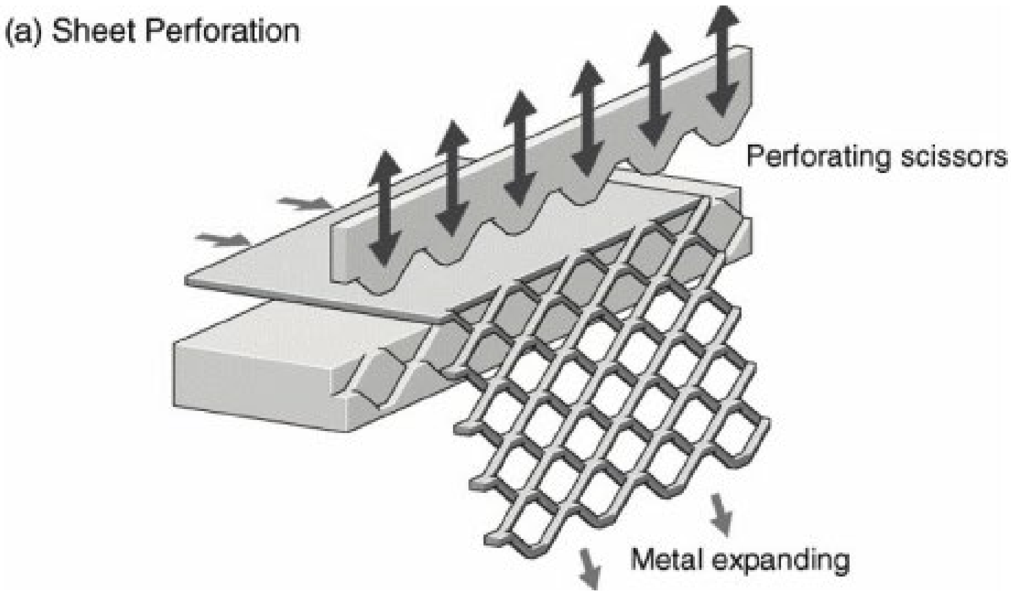


Figure 23: Expanded Metal Mesh Production Explanation, Image Credits: (Graciano, Aparicio, Smith 2015)

Production: *Expanded metal mesh is manufactured with the use of an expanding machine. Metal sheets are fed through the machine to be slit and stretched simultaneously. The result is a mesh product with no joins or welds, formed from a process that produces minimum waste. During the process, the length of the sheet is increased by about 5%, but the width of the sheet remains the same.* [35]

Application: The application of expanded sheet on the building façade is generally made in a modular way. The modules which are customized for each project, are produced in factories, and assembled on site by various details depending on the size. Steel frames on which the modules are bolted or welded are commonly used.

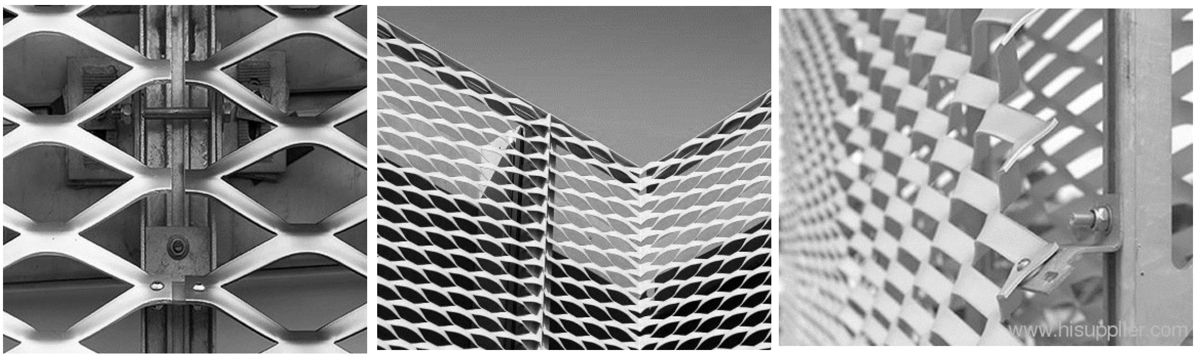


Figure 24: Expanded Metal Mesh Images, Photo Credits: hisupplier.com

The production of the expanded metal mesh is becoming more and more popular as the demand increases. The market of it has been developed so much in the last years that, it is possible to find the EMM that fits each building design in a particular way. The expertise on this field is a great advantage for this material to be chosen as the façade component of the new architectural designs, all around the world.

METHODOLOGY

The main goal of this research can be summarized as to design a geometrically adaptable expanded metal mesh surface which is optimized for various climates by the defined geometrical parameters. A methodology that is based on testing possible configurations that are consisting of the variation of the metal mesh. A daylight simulations tools that is a plug-in of grasshopper called "Honeybee" is used, in order to reach the final goal that is the definition of an optimized expanded metal mesh. The optimization that is done by another plug-in "Octopus" is first achieved with a simple shoebox model, following that 5 case study buildings are examined and optimized to prove the materials' claimed efficiency and as the last step, expanded metal mesh is adapted 3 significant surface typologies and optimized in order to give aesthetical variety to the designer. Finally, a very detailed analysis is made with the eventual "best" models.

During the process it was aimed to seek the answers for these questions:

- How can the shading effect of expanded metal sheets be optimized?
- What are the parameters that affect this optimization?
- How is the adaptation to different climates and surfaces possible?
- What do the results show us? Is this method working well enough to choose EMM as a shading material in buildings?

In the further pages of the paper, all the phases of the process will be demonstrated in a step by step approach.

4. The Process Description

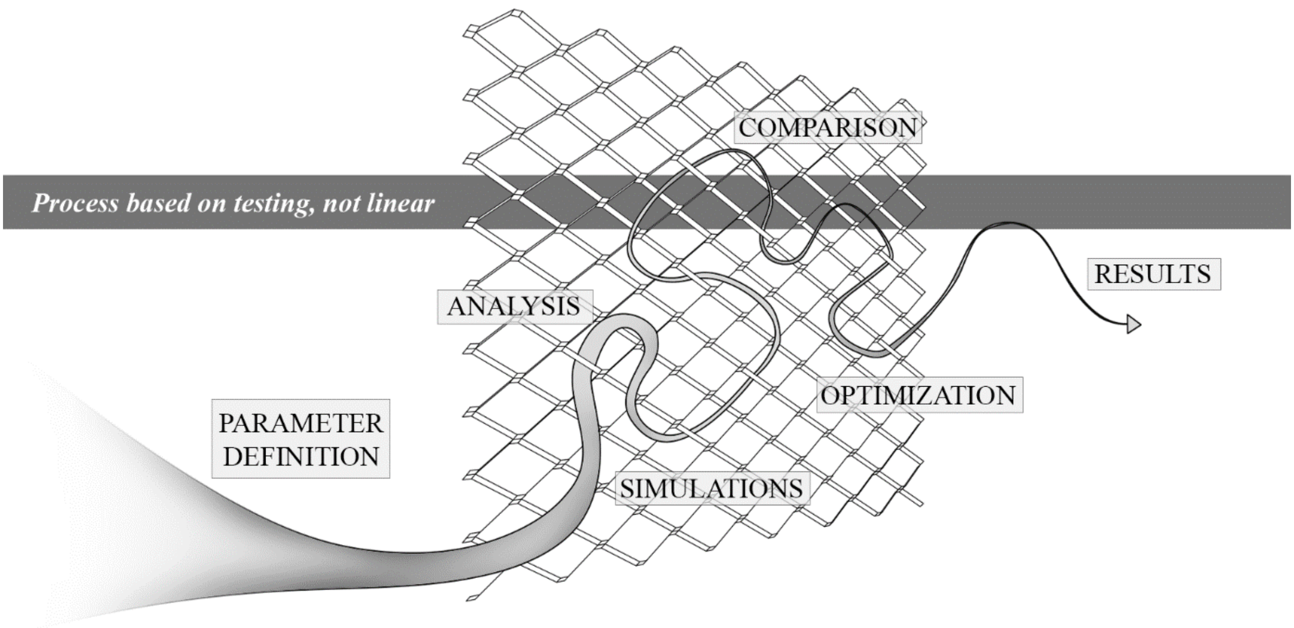


Figure 25: Diagram describing the phases of the process, Photo credits belong to the author

STEP 1: Writing a geometrical script of the expanded metal mesh with the key design parameters

STEP 2: Define the ranges of the geometrical parameters according to the materials' production limitations

STEP 3: Build a simple shoebox model on which the expanded metal mesh is applied

STEP 4: Preliminary daylight simulations, with the critical configurations where the extreme values for each parameter is used and the results are compared to understand the behaviour of the geometry.

STEP 5: Simulate the same configurations within 4 different orientations and significant climates to understand the impact of the location

STEP 6: Find case study buildings which are using the expanded metal mesh as an important element of their building façade

STEP 7: Define their limitations and optimize the material for each of them to compare with the no-shading option + compare with the assumed real design of the mesh

STEP 8: Select one of the spaces that is used for the case study analysis and adapt 3 significant surface typologies to it

STEP 9: Do the optimization for these 3 variations of the final models for the initial 2 climates that are used and for the most critical orientation that is the south

STEP 10: Make a detailed analysis for the "champion" configurations

5. Parametrization of Expanded Metal Mesh

The expanded metal mesh, by its definition, is a material with many qualities and there are a lot of factors which are affecting its performance and many geometrical properties that can be changed. The size of the holes, thickness of the strips and the rotation of the strips can be considered as the main parameters that change according to the users' and building' requirements.

A research is made in order to understand these geometrical parameters that are actually offered by the production companies in the construction market. Here is a summary of them which are offered by the leader firms in the field: [36]

- **Sheet thickness**
- **Shape of holes:** the holes can be cut in different shapaes, diamond, hexagonal, square

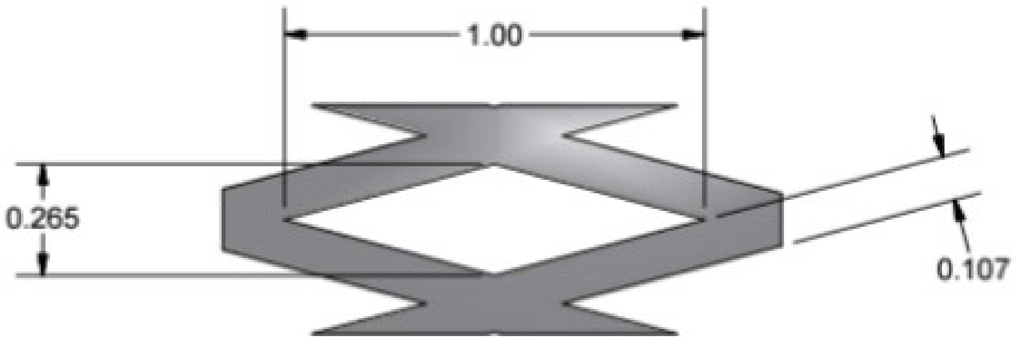


Figure 26: Geometrical Characteristics Description, Photo credits: DIRECT METALS, product catalogue

- **Strands:** This is the term for the solid metal portions of the expanded metal grating. In the image the strands are 0.107" (0.27 cm) wide.
- **Bonds:** This is the term for intersections of strands.
- **Short Way of Design (SWD):** The distance between the centre of bond strands in the mesh when measured along the short diamond diagonal. In the figure above, the SWD is approximately 0.372" (0.94 cm)
- **Long Way of Design (LWD):** The distance between the centre of bond strands in the mesh when measured along the long diamond diagonal. In the figure above, the LWD is approximately 1.107" (2.81 cm)
- **Short Way of Opening (SWO):** The distance between the inside edges between bonds when measured across the short diamond diagonal. The difference from SWD is that SWO measures open space, while SWD measures the space from the centre of one bond strand to the next. In the image above, the SWO is 0.265" (0.67 cm)
- **Long Way of Opening (LWO):** The distance between the inside edges between bond strands when measured across the long diamond diagonal. Like with SWO, the difference between LWO and LWD is that LWO measures open space only, while LWD measures to the centre of a bond strand. In the diagram above, the LWO is 1".(2.54 cm)
- **Strand Thickness:** A measure of the thickness of a strand of expanded metal.
- **Strand Width:** How wide a strand of expanded metal is.
- **Density of openings:** How frequent the holes are
- **Color:** Depending on the color it can have different reflectance aspects [34]

Since the purpose of this research is to optimize these aspects in a computational way, it is very important to simplify the main objectives and write a script in which the mentioned parameters are controlled. Thanks to grasshopper, it was possible to define the expanded metal mesh surface.

The surface definition starts from one module of the mesh that is consisting of a strip that is divided into two part from its middle part and expanded toward the opposite edges. After obtaining this first module, it is repeated in 2 perpendicular directions to create the whole sheet. For the initial simplification model, the parameters that are controlled with the number sliders are;

- **The thickness of the strips**
- **The rotation of the strips**
- **The size of the holes**
  - Long way diamond dimension
  - Short way diamond dimension
- **The size of the complete sheet**

The primary stage of the parametrization is completed by defining the objectives above. In the latter stages these parameters will be simplified further as well as the clear definition of their value ranges depending on the material limitations.

With the image below, it can be observed how the real-life geometry is transformed into a model by the computational design tools.

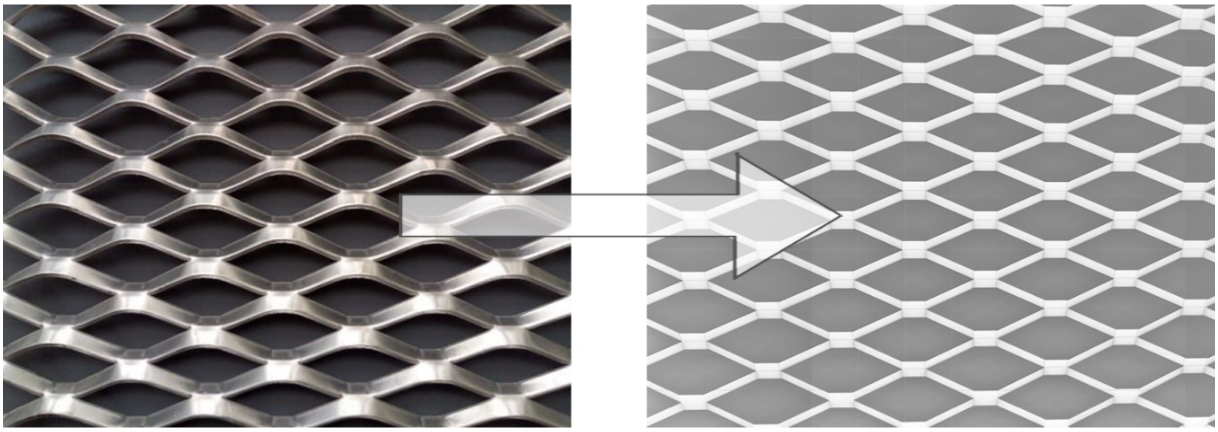


Figure 27: Diagram comparing the real mesh and the modelled mesh, Image credits belong to the author

The transformation has been mainly considering the main characteristics of the EMM, the important parameters which are affecting the daylight performance are defined and highlighted. However, due to the simplification process, the curvature that it has as a result of the expansion process and the thickness of the sheet that was assumed not to have a significant impact, is not present in the research model. It would be an interesting further development if a real-life model having all the necessary properties would be compared with the simplified model to check if the assumptions are correcting and the virtual model is a good representation.

5.1. Geometrical Parameter Limitations

As the first step of the simulation process, two of the significant climate locations are defined and the impact of these parameters are analysed by the definition of three extremes from the defined geometrical parameter ranges (minimum, medium and maximum values for each) as well as considering the orientation differences, for a shoebox model of which the dimensions are represented.

The first thing that was done, was to control and manage the material properties by defining their limitations in a strategic way to be used for the further analysis and simulations. Results are obtained from the information from several production companies and a better average is defined. (The used values are for an average steel product)

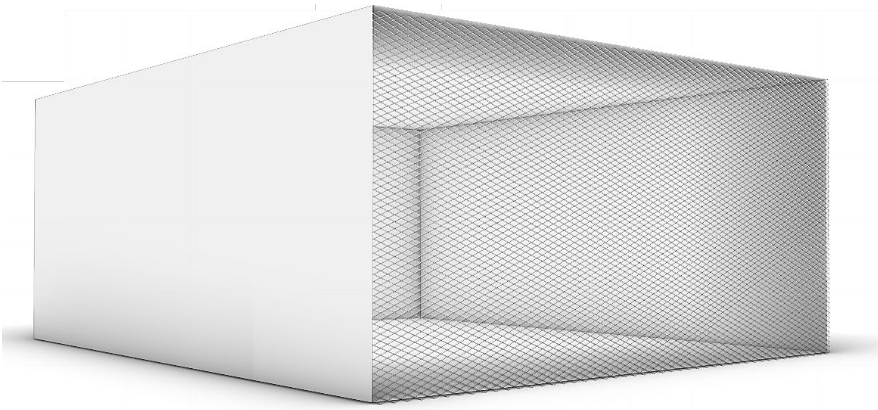


Figure 28: Simulation Model Drawing, Image credits belong to the author

The given limitations of the EMM properties from the production companies (*DIRECT METALS CATALOGUE*) can be summarized as follows,

- Opening ratio can be between **33,3% and 90%.**
- Strip Thickness min. 0.005 m/ max. 0.0180 m
- Size of the opening should be consisting of 2 different values that are defining the distance of both axes.
  - Long way diamond opening distance: **min. 0.031 m/ max. 0.245 m**
  - Short way diamond opening distance: **min. 0.011 m/ max. 0.10 m**
- The rotation of the strips is still between 0 and 85 degrees.

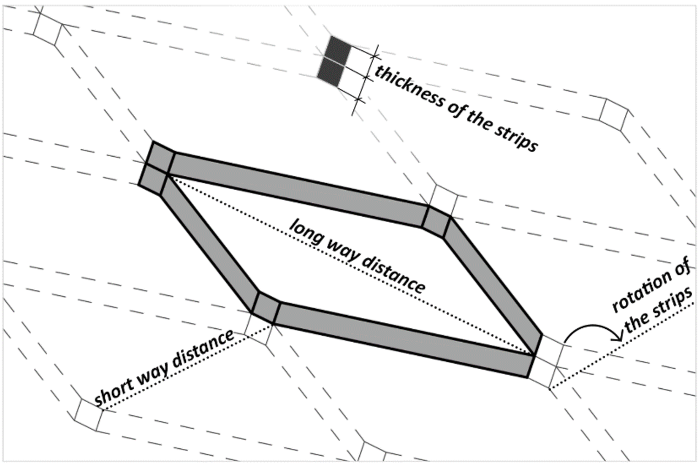


Figure 29: Drawing for the explanation of simplified parameters, Image credits belong to the author

Since there are too many specific parameters; it is necessary to optimize the process further and simplify the inputs more. (so that it is easier and more convenient to work with different surface types as well as other optimization plug-ins)

According the previous preliminary analysis and the nature of the expanded metal mesh itself, the properties that affect the daylight comfort results are the opening ratio as well as the rotation of the strips which changes the results significantly according to the orientation. Thus, the new strategic parameter limitation can be;

- The strip thickness is settled to be **0.011** meters which is the average.
- The rotation of the strips is between 0 and 85 degrees.

However, in order to manage this with a simple method, a proportion between the long way diamond dimensions' minimum and maximum values and the short way diamond dimensions' minimum and maximum values are found which were 2.6 and 2.2. Then the average of these values is obtained to be used as the proportion between them. Thus, the opening is managed to be controlled by a single value that is the size of the short way diamond. **(min. 0.01 m/ max. 0.10 m)**

The other important factor to consider while managing the opening ratio is the visibility. Since proposed system is not a dynamic shading, it is essential to provide the **visual comfort inside at** all times. Visibility, by the definition means, the relative ability to be seen under given conditions of distance, light, atmosphere, etc. It is a very important parameter which architects and engineers are dealing with and simplified terms that is used and required to be satisfied is the **window to wall ratio.** [37] It is an important variable affecting energy performance in a building. Window area will have impacts on the building's heating, cooling, and lighting, as well as relating it to the natural environment in terms of access to daylight, ventilation and views. The window-to-wall ratio is the measure of the percentage area determined by dividing the building's total glazed area by its exterior envelope wall area. [38] For the sake of simplicity, this research will be considering that the building façade on which the expanded metal mesh is applied is already fulfilling this requirement and providing efficient daylight to the indoor space. That is why, the visibility percentage of the shading dee should be controlled in a strategic way meaning that; while improving the illuminance levels and daylight comfort, maintaining the necessary visibility to see outside from the façade. [4]

The visibilities are calculated with the rotation value being 90 degrees meaning that the mesh is considered to be flat so that the indication would be for the worst situation. (Since increasing the rotation also increases the visibility.)

Thanks to the remap component in grasshopper it was possible to change the range of "short way diamond" dimension (0.01-0.1) to the range of visibility percentage (%40-%90).

Below the summary representation of the parameters and the ranges of them within the limitations. All the values inside this range is accepted and the best and the most efficient value is aimed to be found thanks to the simulation and the optimization process.

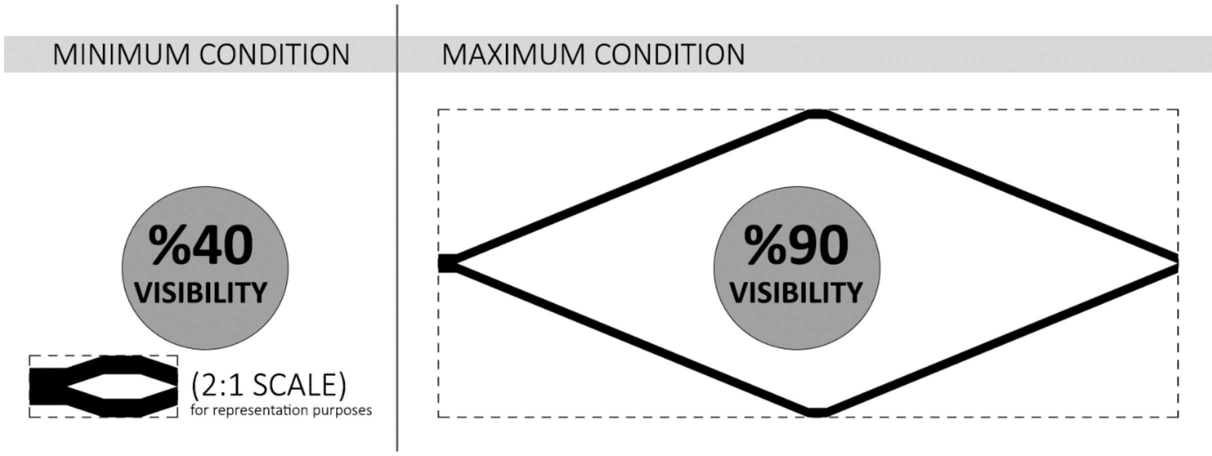


Figure 30: Diagram representing the parameter limitations, Image credits belong to the author

All the steps of this process are made in a parametric way so that the variables are controlled and adapted by the user or the designer. However, for the sake of the simplicity and the understandability of the comparison; some of the parameters have been determined as a fixed input such that their value does not change. The most important parameter like this would be the size of the strips.

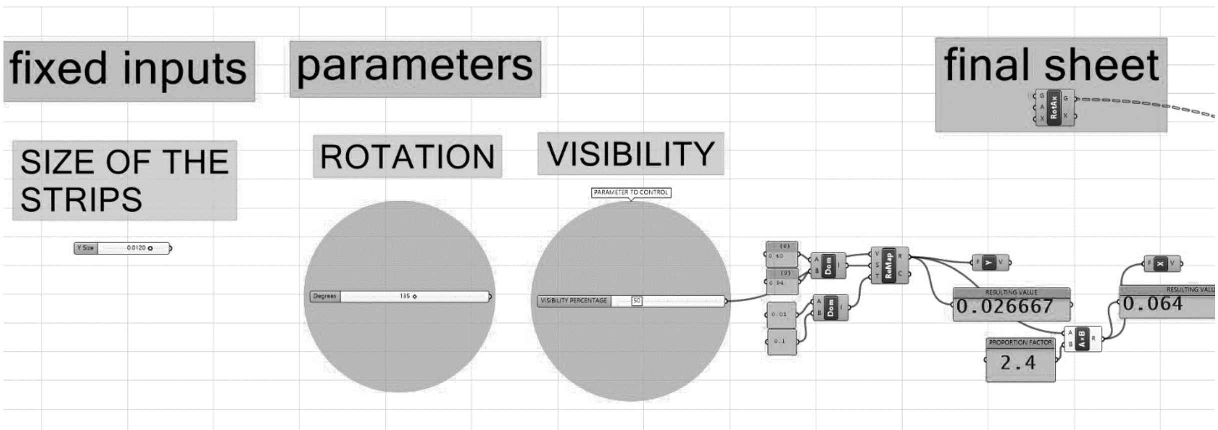


Figure 31: Screenshot from the Grasshopper Script for the Parameter Control

Staring from a point, a rectangle is created on the XY plane. (the thickness of this rectangle defines the “size of the strips parameter). The rectangle is copied first along the X vector, then along the Y vector. Then the original rectangle is mirrored within the axis of the “copied” rectangle. The dimensions between them are defining the “short way diamond distance and the long way diamond distance” parameters; which is converted into the visibility percentage later. Then the rectangles are rotated within their middle line axis that can be controlled by the parameter “rotation of the strips”. This would be the smallest module of the script. Afterwards, this module is copied through the axis of the second rectangle, but also having a movement in the z axis so that the edges of the rectangles are perfectly connected. The latter stages are defined according to the desired surface. For the, preliminary analysis of the flat glazed façade model, the module that is doubled is first move the one of the corners of the mentioned glazing surface. The plane of the module is corralated with the plane of the glazing surface. Then the module is arrayed along both sides of the rectangle. In the diagram below, both all the fixed inputs as well as the variable parameters within their limitations are represented. Moreover, the size of the simple shoebox model which will be used for the preliminary analysis is explained.

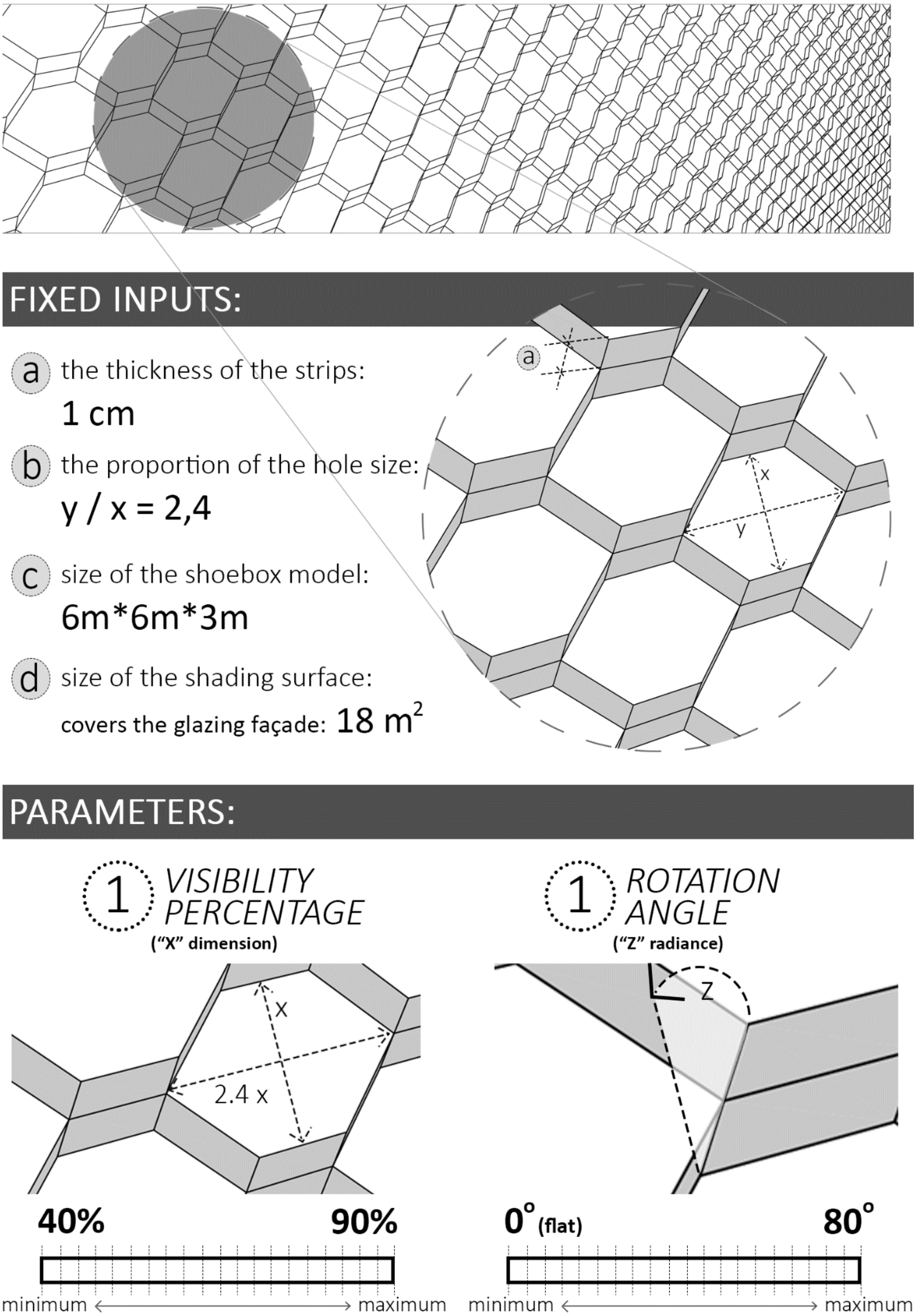


Figure 32: Diagrams describing the inputs used for the analysis, Image credits belong to the author

5.2. Indoor Comfort Daylight Assessment Method

Indoor comfort is the quality of the living environment and the parameters of the building's internal environment. Moreover, the state of mind which expresses the satisfaction with the thermal environment is called “thermal comfort” and is assessed by an evaluation that is subjective (*ANSI/ASHRAE Standard 55*). The human body can be viewed as a heat engine where the food is the input energy. Excess heat is released into the environment by the human body, so that the body can keep on functioning. The heat transfer is proportional to temperature difference. In cold environments, the body loses more heat to the environment and in hot environments the body does not release enough heat. Both the hot and cold scenarios lead to discomfort. Maintaining this standard of thermal comfort for occupants of buildings or other enclosures is one of the important goals of HVAC (heating, ventilation, and air conditioning) design engineers as well as the architects while making decisions that will affect the indoor environment. [39]

One of the most important factors which can be controlled within the design decisions that is affecting the indoor comfort is, without a doubt, daylighting. “Daylight” has a dynamic nature throughout the day and throughout the year. This quality of it presents numerous challenges in the process of designing buildings that seek to utilize this abundant natural resource to meet the architectural space requirements of illuminance levels. This is what defines a good and efficient daylighting design and addresses a general design methodology that considers many different factors. [40]

Psychological and sustainability benefits are the two most important reasons to use daylight in order to meet the illumination requirements of an architectural space. Good daylighting has been shown to significantly improve the overall attitude, satisfaction, and well-being of building occupants. Many research studies are showing that daylighting have variety of benefits in different building types and functions, some of them can be listed as, improved retail sales in big box stores, increased worker productivity and reduced absenteeism in office buildings, improved student educational performance in schools, and improved patient recovery times in hospitals. Improving the general health and the circadian rhythm are the other advantages of exposure to daylight. All these aspects are proving the necessity show and extra importance in design as well as the expenses to introduce controlled daylight into buildings. [21] Moreover, with the proper electric lighting controls the electric loads can be significantly decreased leading the building to have compelling energy savings, regarding the lighting loads, cooling loads and electric loads. In addition, with proper solar control, solar gains during cooling load periods can be mitigated and solar gains during heating load periods can be utilized, reducing the energy requirements of both cooling, and heating a space. [2]

*Some of the key factors in daylighting design is to avoid uncomfortable glare and thermal conditions, as well as veiling reflections and high contrast ratios. These conditions are what creates the poor daylighting conditions where the importance of “**shading methodologies**” emerges as an efficient approach.* [40,41] The recommended approach to daylighting design begins by defining daylighting performance goals and design criteria, and then developing and evaluating daylighting design alternatives that achieve these goals and criteria. Listed below are general daylighting performance goals for daylit spaces that represent successful daylighting design characteristics.

- **Quantity:**
  Provide ambient lighting requirements during daytime hours for the majority of the year.
- **Quality:**
  Create uniform distribution of daylight to reduce uncomfortably high brightness ratios.
  Control direct sunlight when necessary and utilize beneficial passive solar strategies when appropriate.
- **Usability:**
  Allow for user adjustment and override.
  Ensure adequate daylight to all occupants of the daylit space.
  Provide view and connection to the outdoors.
- **Building Integration:**
  Fully integrate with the architectural expression of the building inside and out.
  Fully integrate with other building systems -- HVAC, Electrical, Lighting, Structural, Interiors.
- **Cost Effectiveness:**
  Implement within overall construction budget of the project.
  Achieve significant energy savings by reducing lighting energy costs and associated cooling energy costs.

As the climate, daylight, solar factors are becoming the common issues of this era in the architecture and building field, it is becoming very trendy and necessary to assess and control the daylight as discussed above. That is why, with the new software technologies, many methodologies to evaluate the daylighting strategies have emerges and being used in all around the world. Many planning authorities now require light issues to be addressed as part of a planning application. Daylight modelling software are used to assess a building in detail, together with the effect of surrounding buildings and obstructions. Modelling can highlight the important balance between higher levels of natural daylight in buildings against the additional heating and cooling requirement in spaces with larger areas of glazing. Sunlight and shadow modelling highlight the geometric relationship between the sun and buildings and analysis of this data allows us to be managing the effects of the sun to ensure good building design. [31]

There are so many different methodologies to evaluate and model the daylight, some of the significant ones being; Energy Plus, IESVE, IDA-ICE, Ladybug/Honeybee, Sefaira, Diva; and each of them are working and correlated with different building modelling tools while having variety of advantages and disadvantages.

In this research paper, the main purpose of using one of these tools is to compare many different configurations of shading and to understand the parametrical impact of each geometrical property of expanded metal mesh. It is required to have a simple result to have a fast idea about comfort for the initial stage, then information about how the light is distributed inside the subjected space is crucial.

Having stated these requirements, it was the perfect fit for this research simulations to be made in grasshopper using the plug-in Honeybee and Ladybug that are a part of the Ladybug tools. Moreover, the assessment of the results is made in terms of customized sDA: where the software gives a result that indicates the comfort as well as a coloured mesh that is representing the differences in the architectural space.

What is Honeybee?

Honeybee supports detailed daylighting and thermodynamic modelling that tends to be most relevant during mid and later stages of design. Specifically, it creates, runs and visualizes the results of daylight simulations using Radiance, energy models using Energy Plus/ Open Studio, and heat flow through construction details using Berkeley Lab Therm/ Window. It accomplishes this by linking these simulation engines to CAD and visual scripting interfaces such as Grasshopper/ Rhino and Dynamo/ Revit plugins. It also serves as an object-oriented Application Programming Interface (API) for these engines. For this reason, Honeybee is one of the most comprehensive plugins presently available for environmental design. [43]

What is Ladybug?

Ladybug imports standard Energy Plus Weather files (.EPW) into Grasshopper and Dynamo. It provides a variety of 2D and 3D interactive climate graphics that support the decision-making process during the early stages of design. Ladybug also supports the evaluation of initial design options through solar radiation studies, view analyses, sunlight-hours modelling, and more. Integration with visual programming environments allows instantaneous feedback on design modifications and a high degree of customization. [43]

What is customized sDA?

sDA is a method of climate-based daylight modelling which is the prediction of any luminous quantity using realistic sun and sky conditions derived from standardised climate data. It examines whether a space receives enough daylight during standard operating hours on an annual basis, using hourly illuminance grids on the horizontal work plane.

The main question that sDA asks is “ Is there enough daylight?”. Within the available climate data, for this research EPW files taken from Energy Plus website, sDA is calculates virtually through computational simulation with precise parameters. It references the mentioned local climate file to run hourly illuminance maps in the lighting software packages, in incorporates an algorithm to approximate the manual operation of window blinds.

For the generic sDA analysis; floor areas, or grid points, in the building model that achieve 300 lux for at least half of the analysis hours count as meeting the daylighting threshold. As a result, sDA values can range from zero to 100 percent of the floor area in question. An sDA value of 75 percent indicates a space in which daylighting is “preferred” by occupants; that is, occupants would be able to work comfortably there without the use of any electric lights, and find the daylight levels to be sufficient. An sDA value between 55 percent and 74 percent indicates a space in which daylighting is “nominally accepted” by occupants. Lighting designers, therefore, should aim to achieve sDA values of 75 percent or higher in regularly occupied spaces, such as an open-plan office or classroom, and at least 55 percent in areas where some daylight is important. [33]

However, since this paper is trying to assess the effectiveness of a shading device, it is highly important to have an upper limit for the illuminance values. This is also because of the fact that, one of the main goals of a shading system is to decrease the over-lit areas and avoid the glare problem. To be able to decrease the illuminance levels that are exceeding the comfort according to the functional requirements, is a focal point for this research. That is why instead of using the generic proposed sDA ranges; customized thresholds have been used. And these thresholds are changed depending on the function that the subjected space has. Below, the applied chart which is made by “Engineering Toolbox” community is represented.

Activity	Illuminance (lx, lumen/m²)
Public areas with dark surroundings	20 - 50
Simple orientation for short visits	50 - 100
Areas with traffic and corridors - stairways, escalators and travelators - lifts - storage spaces	100
Working areas where visual tasks are only occasionally performed	100 - 150
Warehouses, homes, theaters, archives, loading bays	150
Coffee break room, technical facilities, ball-mill areas, pulp plants, waiting rooms,	200
Easy office work	250
Class rooms	300
Normal office work, PC work, study library, groceries, show rooms, laboratories, check-out areas, kitchens, auditoriums	500
Supermarkets, mechanical workshops, office landscapes	750
Normal drawing work, detailed mechanical workshops, operation theaters	1000
Detailed drawing work, very detailed mechanical works, electronic workshops, testing and adjustments	1500 - 2000
Performance of visual tasks of low contrast and very small size for prolonged periods of time	2000 - 5000
Performance of very prolonged and exacting visual tasks	5000 - 10000
Performance of very special visual tasks of extremely low contrast and small size	10000 - 20000

Table 1: Illuminance levels depending on the activity, Credits: http://www.engineeringtoolbox.com/light-level-rooms-d_708.html

Thus, the result that the simulation is giving to us is the percentage of the defined horizontal surface of the shoebox model, that is in the comfort range for more than 50% of the time.

The passages that are made and the components that are used for the honeybee analysis is represented below.

First the Honeybee Zone is defined by the components of the model which are the walls, floors, glazing and finally the shading. Then the mesh, on which a grid would be defined, and the preciseness of the simulation would be determined is placed, having the same dimensions of the floor of the model. However, the position of this mesh is moved to a higher level than the ground (0.750 m) that is the general usage of the work plane. The component where the weather data is introduced is defined as well as the vector that defines the north vector. Then the honeybee annual daylight analysis components are introduced to the script and all the necessary information is connected within these components. Number of CPU is defined as 8 to have faster results. Afterwards, the illuminance thresholds are determined within the mesh that is defined for the analysis. Then the result is read both in terms of a coloured mesh that represents the comfort levels in each pixel of the grid and also in terms of a single number that is showing the Customized Spatial Daylight Autonomy.

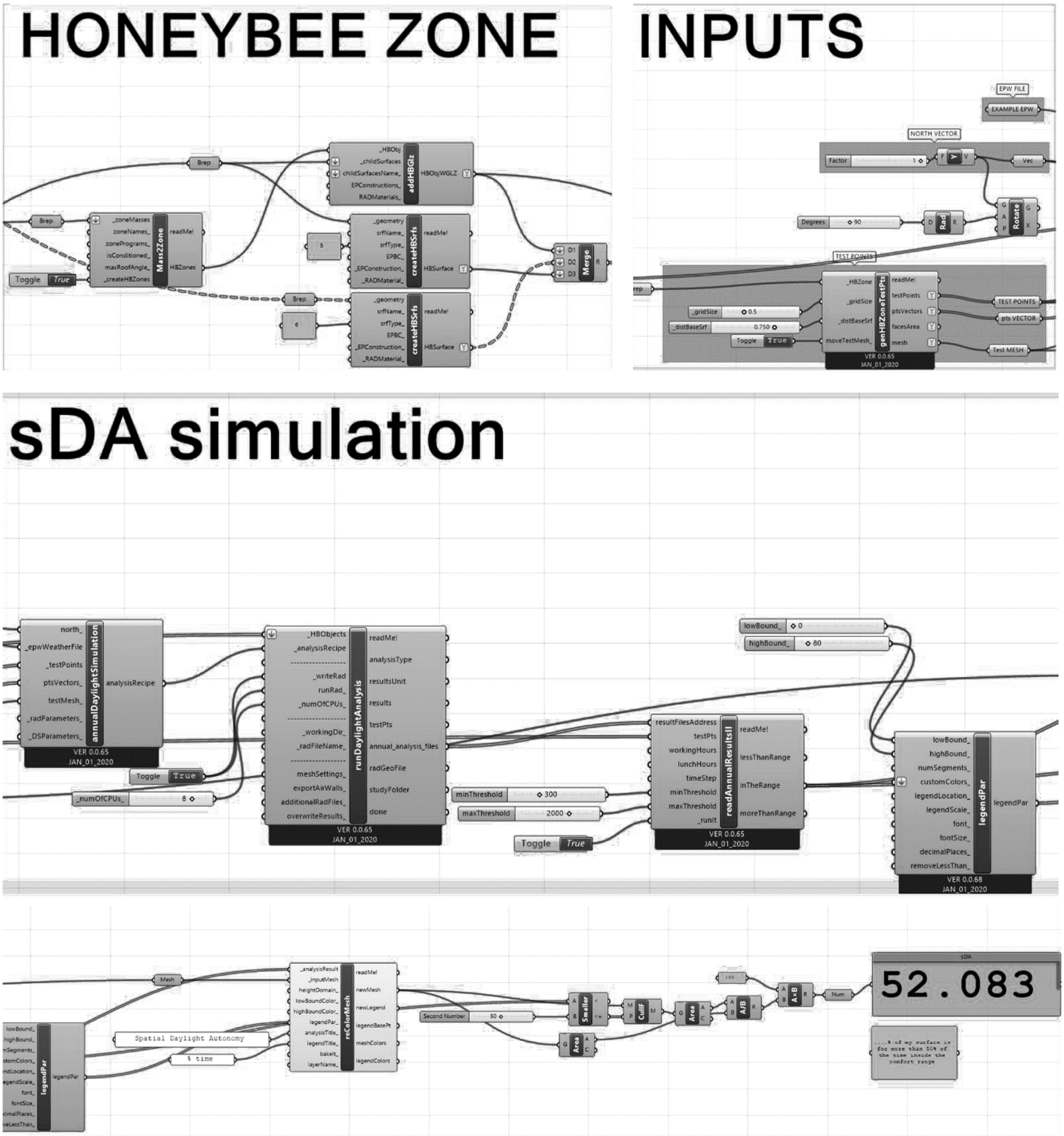


Figure 33: Screenshots from the Grasshopper script of the Honeybee Analysis

5.2.1. Possible Assessment Results

As mentioned in the previous chapter, sDA analysis gives important and useful results to be used in the daylighting design process. For the comparison part of this research, the assessments of the results will be conducted to present the significance of the shading impact of the expanded metal mesh. However, the customized spatial daylight autonomy is not the only assessment methodology that needs to be analysed. While going into more detail with the further studies and simulations; it is crucial to understand what grasshopper and the used plug-ins can offer us.

Here is a summary of the values that are most commonly used in the field. [43,44]

ILLUMINANCE BASED METRICS

LUX is the SI derived unit of illuminance and luminous emittance, measuring luminous flux per unit area.

DAYLIGHT FACTOR (DF): It is the measure of the amount of illumination available indoors relative to the illuminance present outdoors at the same time under overcast skies.

$$daylight\ factor = \frac{inside\ illuminance}{outside\ illuminance} * 100$$

This value is independent from the building site and the time of the day of analysis which actually are key design parameters. This fact leads to two sources of uncertainty to predict indoor illuminance that are the fluctuation in the total amount of light penetrating a cloudy atmosphere and the fluctuation in the sky's brightness pattern. It is best considered as an indicator of the performance of the room when the sky is overcast.

CLIMATE BASED DAYLIGHT MODELLING

It is the prediction of the luminous quantity using the realistic sun and sky conditions derived from standardized climate data, generally for a full year.

SPATIAL DAYLIGHT AUTONOMY (sDA): It examines whether a space receives enough daylight during standard operating hours on an annual basis, using hourly illuminance grids on the horizontal work plane. Floor areas or grid points in the building model which achieves 300 lux (based on legislation) for at least half of the analysis hours count as meeting the daylight threshold. That is why, sDA can range from 0 to 100 percent of the floor area in question.

$$sDA > 75\% * preferable *$$

$$55 < sDA < 74\% * acceptable *$$

The aim of the designers should be to reach values of 75% or higher in regularly occupied spaces. Lighting designers can use this value to compare different spaces on the same daylighting terms.

ANNUAL SOLAR EXPOSURE (ASE): The potential of glare and solar heat gain occurs with the higher levels of daylight sufficiency. That is where the ASE has the importance, also to compliment sDA. This value intends to help designer limit the excessive sunlight in a space. While it is a crude proxy for the glare problem, it measures the presence of sunlight using annual hourly horizontal illuminance grids rather than luminance measures. That is why it is not a glare metric. ASE uses a simulated 1000 lux as an indicator value for sunlight. However, the simulated value can differ a lot due to real measurements that consider secondary bounce-off surfaces.

ASE value is ranging from 0 to 100 percent as well. With the latter suggesting that the entire floor area of the space in question exceeds simulated value of 1000 lux for at least 250 hours per year. Moreover, to reduce the potential for glare and thermal stress; the designers should aim for low ASE values.

USEFULL DAYLIGHT ILLUMINANCE (UDI): This metric bin hourly time values based upon 4 illumination ranges; 0-100 lux, 100-300 lux, 300-3000 lux, and over 3000 lux. The full credit is provided only to values between 300-3000 lux, indicating that values outside this range are not useful. Above 3000 lux in an area is considered to have potential glare or overheating problem.

DAYLIGHT AUTONOMY (DA): It is the percentage of annual daytime hours that a given point in a space is above a specified illumination level. It can also relate to the electric energy savings if the criteria are based upon electric lighting criteria. The thresholds can be defined by the user.

CONTINUOUS DAYLIGHT AUTONOMY (cDA): This value provides a linear trend to values below the threshold that is defined by the user. For example, if 300 lux were specified as the DA threshold and a specific point exceeded 300 lux, 50% of the time on an annual basis; the cDA300 might result in a value of approximate 50-60% or more.

(definitions are taken from the "Adaptive Façade Studio" course 2020, presented by Prof. Marco Pesenti, Politecnico di Milano - Msc. Building Engineering)

The significant measurement/assessment methods used in the market are summarized above. As it is stated, each of them has advantages and disadvantages within their considerations. For this thesis, the Spatial Daylight Autonomy have been found useful for the comparison of the configurations. This is due to the fact that, it is defining the annual comfort level taking into account the illuminance levels that can be determined by the user. (the maximum and minimum values). Moreover, since the considered expanded metal mesh design is a static one, an annual value would be the most beneficial method of assessment for this case.

5.2.2. Optimization Methodology

Optimization is an act, process, or methodology of making something (such as a design, system, or decision) as fully perfect, functional, or effective as possible. The aim of this thesis is to achieve this optimization of the EMM in terms of daylight comfort. As the possible methods to measure the daylight comfort are explained in the previous chapter; there are many ways to assess and compare the results would be obtained by the optimization simulations. These simulations are going to be made within the aim of finding the “better” configuration for the expanded metal mesh. Which is why, a metric which is directly stating the daylight comfort inside is determined to be selected. Spatial Daylight Autonomy is providing this aspect by giving a percentage of time (during the working hours) that is in comfort. However, how this comfort is defined would be the main question, since the illuminance range that implies it is only defined with a lower range, while the assessment of a shading device should be made also by perceiving the decrease on the over-lit areas. The existing metric of the sDA is not providing this aspect that is very important for the methodology of this thesis. That is why, it has been decided that a CUSTOMIZED SPATIAL DAYLIGHT AUTONOMY measurement system is decided to be used where both the lower and upper threshold for the comfort illuminance range inside is implied.

For this particular analysis, it was aimed to do an optimization of the expanded metal mesh with regards to the daylight comfort. Moreover, the goal is to optimize the defined parameters which are “VISIBILITY PERCENTAGE” and “THE ROTATION OF THE STRIPS” while maximizing the “CUSTOMIZED SPATIAL DAYLIGHT AUTONOMY” value to have the best amount of indoor comfort.

Having mentioned the main scope of the optimization, the most convenient tool for it was “**OCTOPUS**”, which is a plug in for grasshopper.

What is Octopus?

Octopus was originally made for **Multi-Objective Evolutionary Optimization**. It allows the search for many goals at once, producing a range of optimized trade-off solutions between the extremes of each goal. It is used and works similar to David Rutten's **Galapagos**, but introduces the **Pareto-Principle for Multiple Goals**.

- search for single goal + diversity of solutions
- search for best tradeoffs between 2 to any number of goals
- improve solutions by similarity-goals

The development of Octopus is partially based on research and practice previously undertaken at Bollinger-Grohmann- Schneider ZT GmbH Vienna and the Institute for Structural Design at the University of Applied Arts Vienna. Their fields of application relevant for this work lie in complex building-geometries and algorithmic approaches to generate and optimize them. Since 2008, several generative, analytic, and optimization tools have been developed which provide useful resources and experience. [44] Octopus is built as a plug-in for the graphical parametric modelling environment of Grasshopper, but it could be implemented to frameworks with similar architecture relatively easy. The encapsulated software design pattern also allows an easy exchange of the multi-objective optimization algorithm operating at the core. A restraint in this particular implementation is the interface to Grasshopper in terms of computational performance: An evolutionary algorithm, though using meta-heuristic strategies, relies on the evaluation of many possibilities to find good solutions. [20]

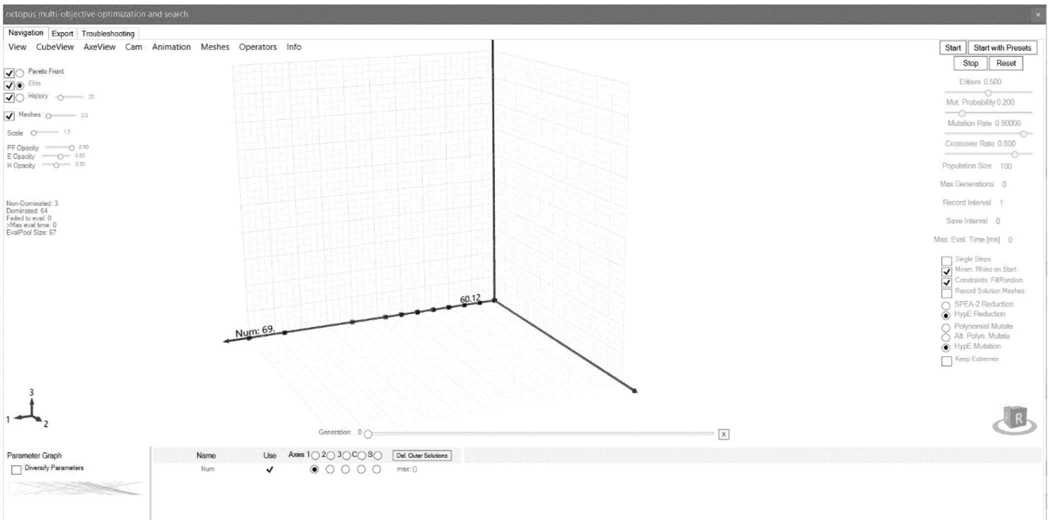


Figure 34: Screenshot from the Octopus Plug-in optimization graph

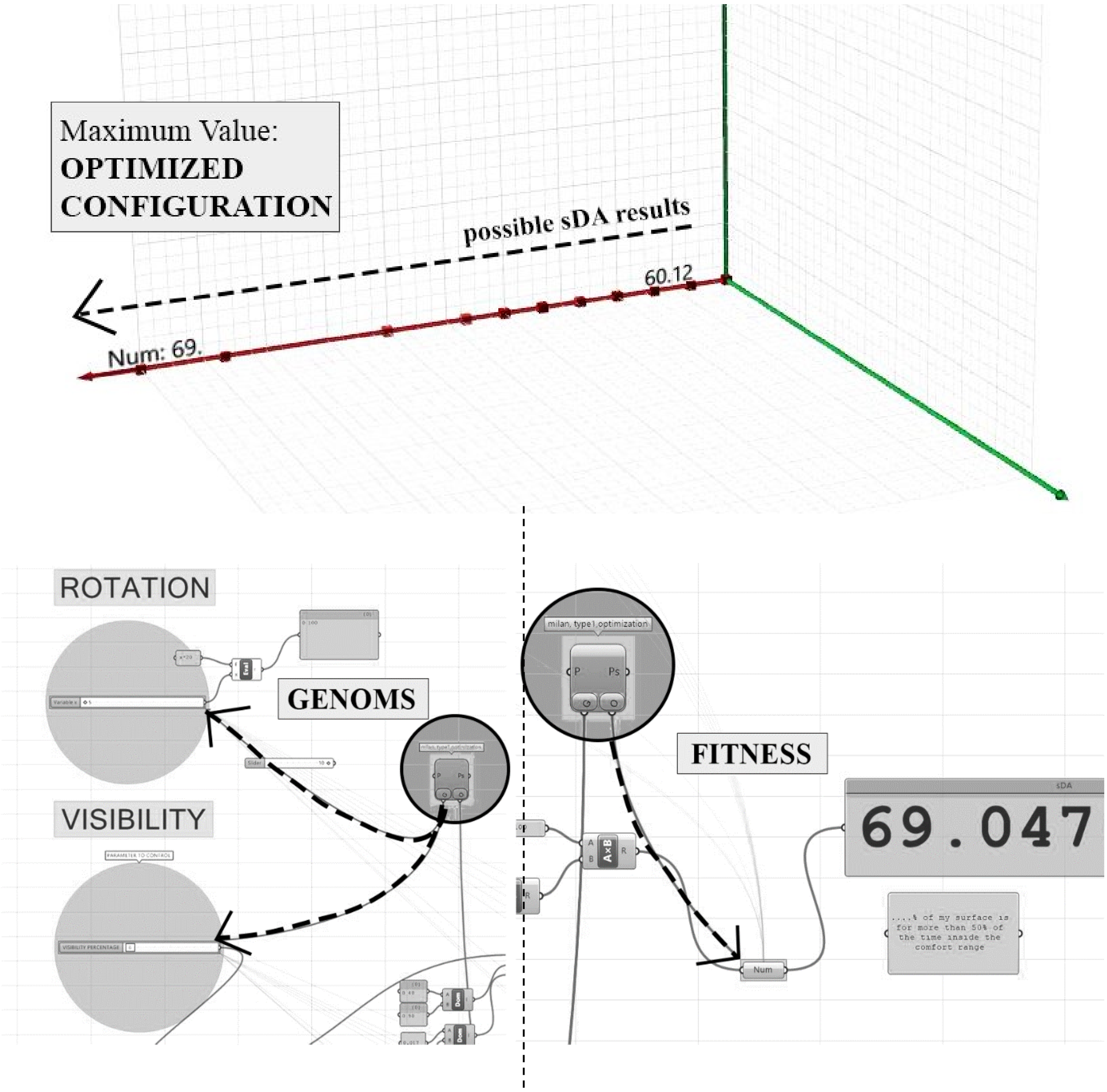


Figure 35: Screenshots from the Grasshopper script for Octopus Optimization

The images above are the screenshots from the process of the Octopus optimization. As explained within the definition of octopus, the component needs two objectives called “fitness” and “genome”. Genome parameters are the ones that we would like to optimize the values of, so for this case are the “visibility percentage” and the “rotation of the strips”. The second one, fitness, is the resulting value that need to be either maximized, minimized, or found within a range. For the case, since the resulting is defining the comfort, it is maximized. After connecting these to the octopus simulation component, it is necessary to run the simulation once manually, then double click on the component so that the window that is shown in the first screenshot image appears.

Octopus does a very high number of analysis to find the maximum value of the fitness meaning the customized spatial daylight autonomy. To do so, it tries all the values within the ranges of the genomes and their combinations, meaning that for the visibility percentage parameter it tries all the values between 40 and 90 that is 50 values in total, and for the rotation of the strips, between 5 and 85 meaning 80 values. Thus, the number of combinations that octopus requires to make is 4000. Considering that each simulation takes around 850 second to be finishes. It was not convenient to use the parameters like this. That is why, a simplification is made which is to reduce the number of options by defining the number slider of the parameters out of snapping factored values. For both of the parameters, the factor is defined as 5 and all the values that are simulated as the multiplication of it.

In the second image, the in which Octopus is giving results is represented. Since for this process there is only one value to optimize the results are shown in a linear line. If the aim were to optimize two or more values the dimension of the value representation would have changed to 2D or 3D.

For each optimization, the average time that is given is approximately 15 hours. Since there are so many configurations to analyse, octopus generally never stops simulating, which is why it is important to know what to expect from the results and control the process in an efficient why. For the case of the expanded metal mesh optimization, optimized results very obtained within the time frame of 15 hours and the simulations are stopped. The maximum value that is given in the red line is selected and analysed further to observe the parameter values that are making this optimized configuration possible.

6. Preliminary Shoebox Analysis

In this chapter of the research, the preliminary shoebox simulations will be explained. The flat shoebox analysis had been chosen as the initial step in order to have an initial idea of how the parameters are actually working and how they are affecting the daylight comfort inside.

Shoebox Analysis is an important step for the daylight simulations. Even though the created model is much simpler, the results can give very useful ideas about how the actual space would react. The advantages of shoebox modelling are as follows; [45]

- investigate a specific portion of a building to improve local comfort or energy use
- exclude the rest of the building from your model
- use automated versions of shoebox modelling with reasonable default inputs

- perform daylight performance modelling when you do not have a developed design
- can start this whole process with very little information

To be able to use the advantage of these simulations, it is important to know what the determined inputs and the variables are so that the results are controlled and expected. That is why, the definitions about the model are very important. Since this first step is mostly about the comparison of the parameter values meaning the reaction in terms of customized spatial daylight autonomy when the geometrical inputs change; a critical schedule had to be done before.

6.1. Input Definitions

As mentioned in the previous chapter, both the **variables** and **fixed inputs** are very important, for designers to understand results of the simulations.

VARIABLES

In the chapter "Geometrical Parameter Limitations", the simplification methodology for the variables were explained. It can be summarized that the controllable variables are;

- **The visibility percentage:** (which is a proportioned parameter of the long way diamond distance and short way diamond distance) **40%-90%**
- **The rotation of the strips** (the angle of the strip with regards to a plane parallel to the glazing) **5 degrees-85 degrees**

FIXED INPUTS

1. LOCATION

In this stage of the research it was also useful to understand the impact of the climate and how the expanded metal mesh performance is affected by it. That is why, two locations from Europe are selected which are both capitals and have different climatic properties: Milano and Oslo.

Milano Climate: Milan lies on 133m above sea level In Milan, the climate is warm and temperate. The rainfall in Milan is significant, with precipitation even during the driest month. The climate here is classified as Cfa by the Köppen-Geiger system. The average temperature in Milan is 13.1 °C. About 1013 mm of precipitation falls annually. *(Wikipedia)*

Figure 36: Photo from Duomo, Milano, Image credits: https://www.hurriyet.com.tr/seyahat/yazarlar/serhat-sarisozen/italyanin-sik-sehri-milano-41312186

Milan's climate is similar to much of Northern Italy's inland plains, with hot, humid summers and cold, foggy winters. The Alps and Apennine Mountains form a natural barrier that protects the city from the major circulations coming from northern Europe and the sea.

During winter, daily average temperatures can fall below freezing 0 °C and accumulations of snow can occur: the historic average of Milan's area is 25 centimetres in the period between 1961 and 1990, with a record of 90 centimetres in January 1985. In the suburbs the average can reach 36 centimetres. The city receives on average seven days of snow per year.

Oslo Climate: Here, the climate is cold and temperate. The rainfall in Oslo is significant, with precipitation even during the driest month. The climate here is classified as Dfb by the Köppen-Geiger system. The temperature here averages 6.3 °C. In a year, the rainfall is 740 mm.

Figure 37: Photo from Oslo, Image credits: https://www.silversea.com/cruise-to/oslo.html

Oslo has a humid continental climate (Köppen climate classification: Dfb) with warm summers and cold winters. Due to oceanic influences, winters are less cold than more continental areas at same latitude, but still cold enough to be continental. Oslo has a significant amount of rainfall during the year. This is true even for the driest month. Because of the city's northern latitude, daylight varies greatly, from more than 18 hours in midsummer, when it never gets completely dark at night (no darker than nautical twilight), to around 6 hours in midwinter. *(Wikipedia)*

2. THE ORIENTATION

Similar to the climate, orientation was one of the key factors that would affect the behaviour of expanded metal mesh, which is why it is that, all four possibilities, **NORHT, SOUTH, EAST** and **WEST**, would be analysed and the most effective and efficient one will be selected for the further stages of the simulations.

3. SHOEBOX MODEL

The modelling and dimensioning of the shoebox is a very important step for the daylight simulations since the size and depth of the space are determining the results. The shoebox as well is introduced in a parametric way in grasshopper, so that it can change according to the necessities and the shading surface can be connected and scaled along with the glazing surface.

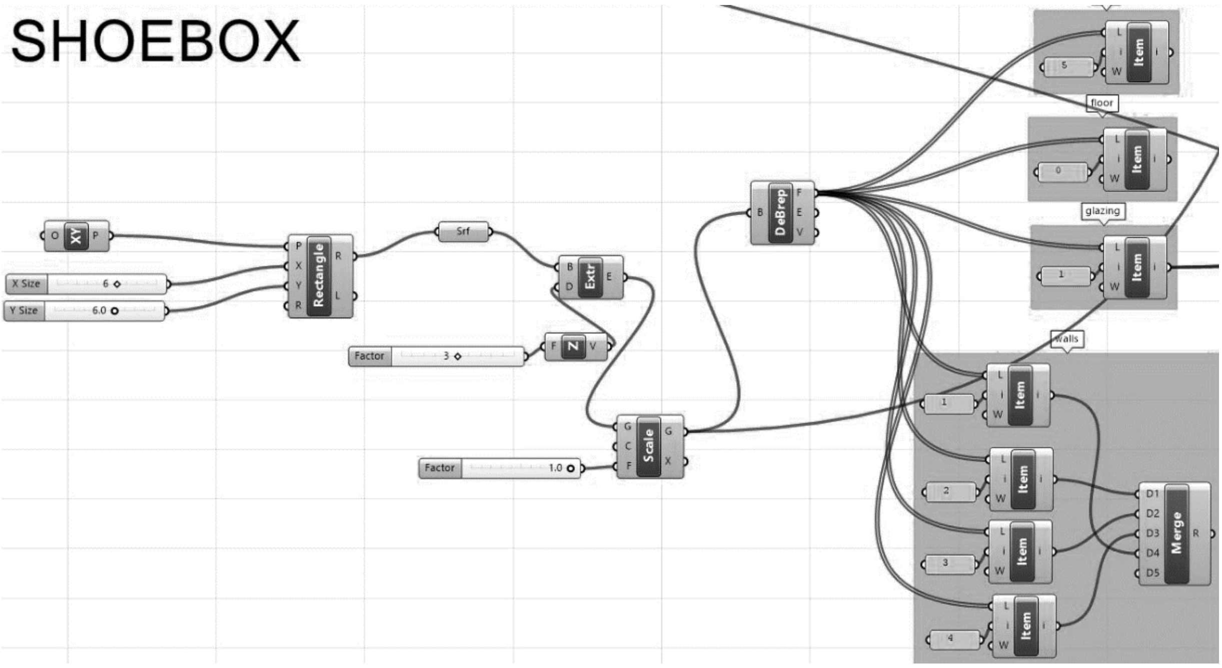


Figure 38: Screenshot from the grasshopper script for the shoebox modelling

The image above is the representation of the script where the dimensions of the shoebox is controlled.

The depth of the shoebox model plays an important role for the results of the simulations. The deeper the space, the less daylight to be able to reach which increases the amount of under-lit areas. That is why a strategic dimensioning is selected with proportion to the glazing surface height.

The maximum room depth should be 2 to 2.5 times window head height for continuous fenestration and curtain wall constructions.

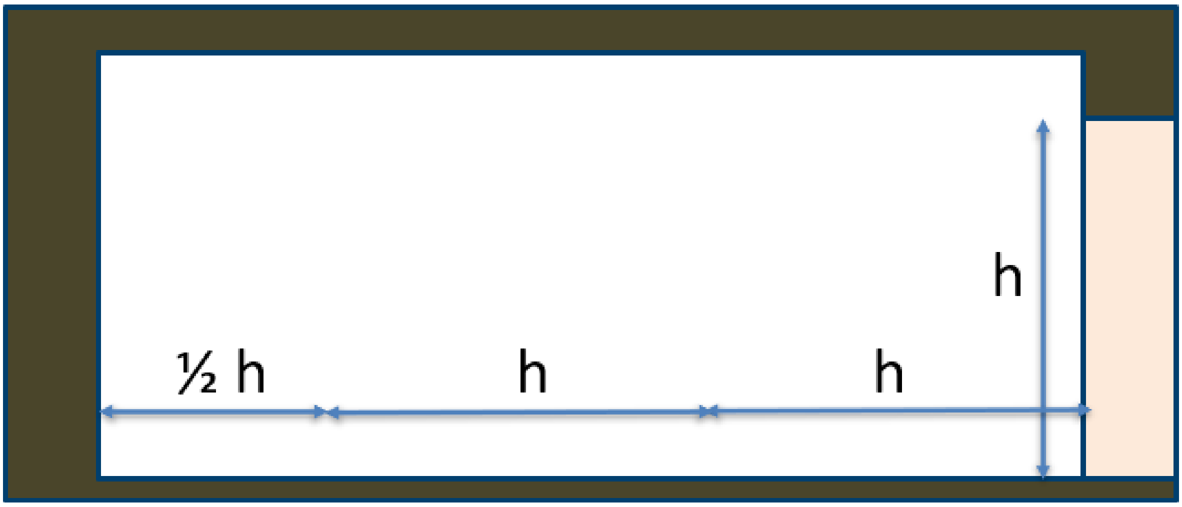


Figure 39: Shoebox Modelling Standards

Not only the size of the shoebox, but also how it should be introduced to the Honeybee simulation components play an important role for the results. Here is a summary of all the inputs that are used:

- Floor area: **36 m²**
- Depth of the space: **6 m**
- Height of the space: **3 m**
- Glazed area: **18 m²** (the same size as one of the façades)
- The grid mesh location: **0,75** meters above the floor
- The grid size: **0,5*0.5** m
- The components of the model: **2 parallel floors, 4 walls, 1 glazing surface, Shading surfaces**
- Shading surface type: **Flat**

REFLECTANCE PROPERTIES OF THE HONEYBEE ZONE COMPONENTS: The effect a lighting system creates in an interior is strongly influenced by the properties of the room surfaces. Surface Reflectance greatly assists with light levels. Areas with low reflectance levels need more light to achieve the same lux levels. Indirect Light works very well in areas with high reflectance surfaces. High reflectance areas soften shadows. In contrast, low reflectance surface accentuates shadows. [43]

- **The floors:** ***0,2*** (White Paint on Non-fines Concrete)
- **The walls:** ***0,5*** (concrete wall system)

- **The shadings:** Total Solar Reflectance: ***0,66*** / Light Reflectance Value: ***0.67*** (*the SandScape® coating from ColorSteel have been used the value is obtained from the user's guide*)

The properties of the glazing that is used for the simulation are also important to be identified, since they are affecting the daylight performance of a space. The goal of these simulations is to understand the impact of EMM as a façade component and exploit its performance, which is why the quality of the glazing was not the focal point. The simple, single pane clear glazing panel system that is defined in the default material library of Honeybee is used having the properties listed below: [43]

- **Thickness**: Number for the thickness of the glass layer [m] ***0.003 meters***
- **Solar Transmittance**: The transmittance of solar radiation through the glass at normal incidence. ***0.85***
- **Solar Reflectance**: The reflectance of solar radiation off of the front side of the glass at normal incidence, averaged over the solar spectrum. ***0.075***
- **Visible Transmittance**: The transmittance of visible light through the glass at normal incidence. ***0.9*** (equal to a single pane clear glazing surface)
- **Visible Reflectance**: The reflectance of visible light off of the front side of the glass at normal incidence. ***0.075***
- **Infrared Transmittance**: Long-wave transmittance of the glass at normal incidence. ***0***
- **Emissivity**: The infrared hemispherical emissivity of the front side of the glass. ***0.84***
- **Emissivity Back**: The infrared hemispherical emissivity of the back side of the glass. ***0.84***
- **Conductivity**: Number for the thermal conductivity of the glass [W/m-K]. ***0.9***
- **SHGC**: Solar heat gain coefficient of the glazing system. This includes both directly transmitted solar heat as well as solar heat that is absorbed by the glazing system and conducts towards the interior. ***0.86***

The next image is showing the visual representation of the preliminary flat shoebox which the first analysis is made with.

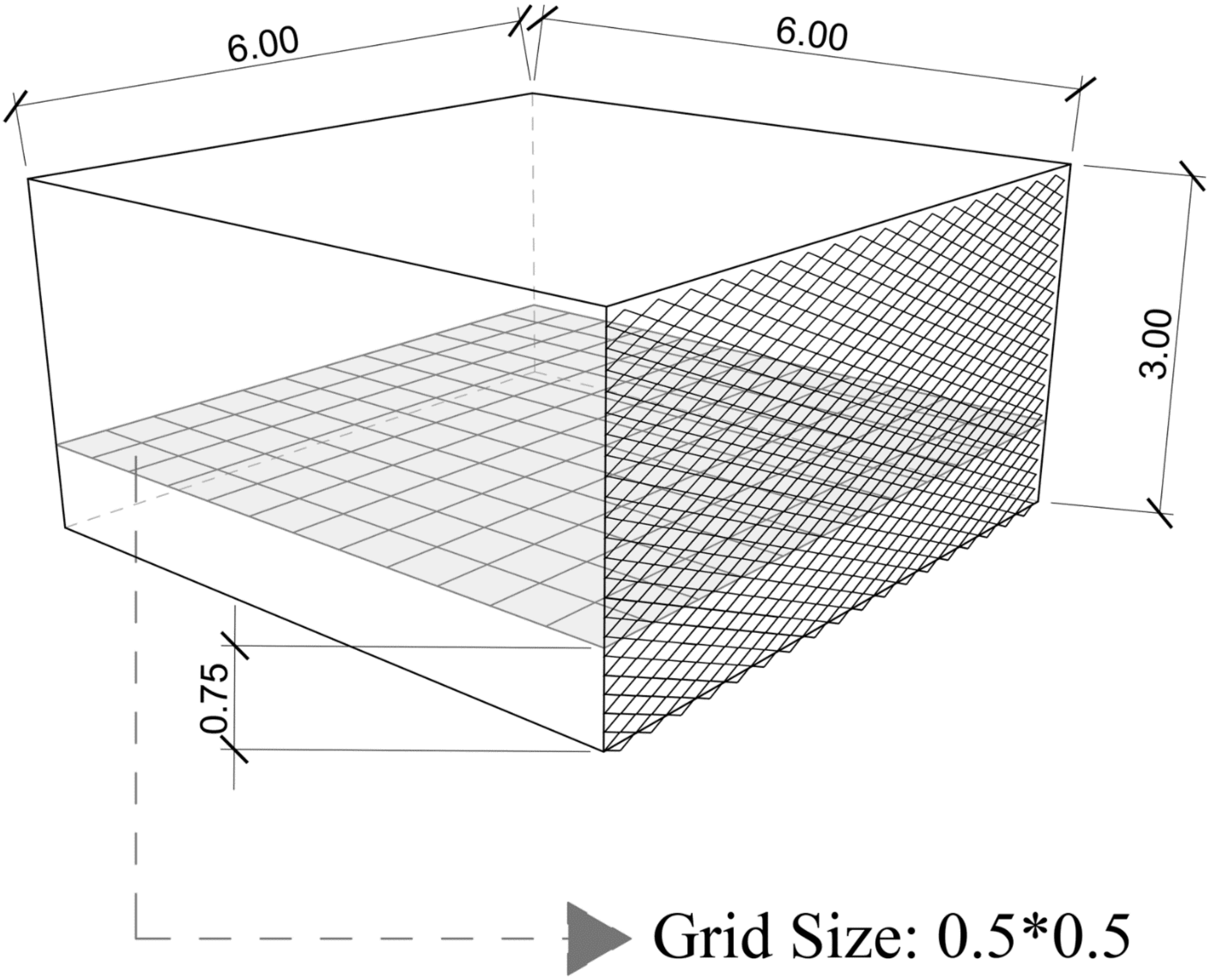


Figure 40: Drawing indicating the shoebox model characteristics, Credits belong to the author

4. FUNCTION and ILLUMINANCE LEVEL

The comfort range of illuminance level depends on the function that is attained to that space according to its necessities. That is why, it is crucial to comprehend the activities that will take place in the room and understand its lighting requirements.

According *EN 12464 Light and lighting - Lighting of workplaces -Indoor workplaces,* the minimum illuminance is 50 lux for walls and 30 lux for ceilings. Earlier it was common with light levels in the range *100 - 300 lux* for normal activities. Today the light level is more common in the range *500 - 1000 lux* - depending on activity. For precision and detailed works the light level may even approach *1500 - 2000 lux*. [46]

As mentioned in the previous chapter, for the analysis of expanded metal mesh, customized threshold values are used. The thresholds for the interior lux levels were found from these charts which are indicating the comfort levels. This first shoebox model is done only to compare the parameters, that is why, instead of choosing a specific function and use its threshold values, the range is created as the minimum value being taken from the legislation while the maximum one is obtained by the average of different functions' values.

Activity	Illuminance (lx, lumen/m²)
Public areas with dark surroundings	20 - 50
Simple orientation for short visits	50 - 100
Areas with traffic and corridors - stairways, escalators and travelators - lifts - storage spaces	100
Working areas where visual tasks are only occasionally performed	100 - 150
Warehouses, homes, theaters, archives, loading bays	150
Coffee break room, technical facilities, ball-mill areas, pulp plants, waiting rooms,	200
Easy office work	250
Class rooms	300
Normal office work, PC work, study library, groceries, show rooms, laboratories, check-out areas, kitchens, auditoriums	500
Supermarkets, mechanical workshops, office landscapes	750
Normal drawing work, detailed mechanical workshops, operation theaters	1000
Detailed drawing work, very detailed mechanical works, electronic workshops, testing and adjustments	1500 - 2000
Performance of visual tasks of low contrast and very small size for prolonged periods of time	2000 - 5000
Performance of very prolonged and exacting visual tasks	5000 - 10000
Performance of very special visual tasks of extremely low contrast and small size	10000 - 20000

Figure 41: Illuminance levels depending on the activity, Credits: http://www.engineeringtoolbox.com/light-level-rooms-d_708.html

- Min. illuminance: 250 lux (from legislation)
- **Max. illuminance: 2000 lux** (an average value for various spatial functions)

250 lux<**COMFORT**<2000 lux

This range will be defined in the simulation script as the comfort levels for the annual calculation of the Customized Spatial Daylight Autonomy. The CsDA simulation will calculate for how much time of the year, the test points in the analysis mesh, have illuminance levels inside this range.

The analysis variations that are represented below are made on the purpose of understanding impact of the geometrical parameters on different orientation and climates. Even though it is important to analyse the relationship between them, for the sake of simplicity; while varying one parameter, the medium value will be used for the others. Moreover, the medium values for each section can be considered as the reference to comment on the results. As mentioned before, 3 values are selected from the ranges and 5 different configurations have been simulated, in 4 orientation and 2 locations; Oslo and Milano. In total, there were 40 analysis made for the configurations with EMM and 8 configurations for each condition without any shading device applied. This chart is showing all the different options and their formal translation.

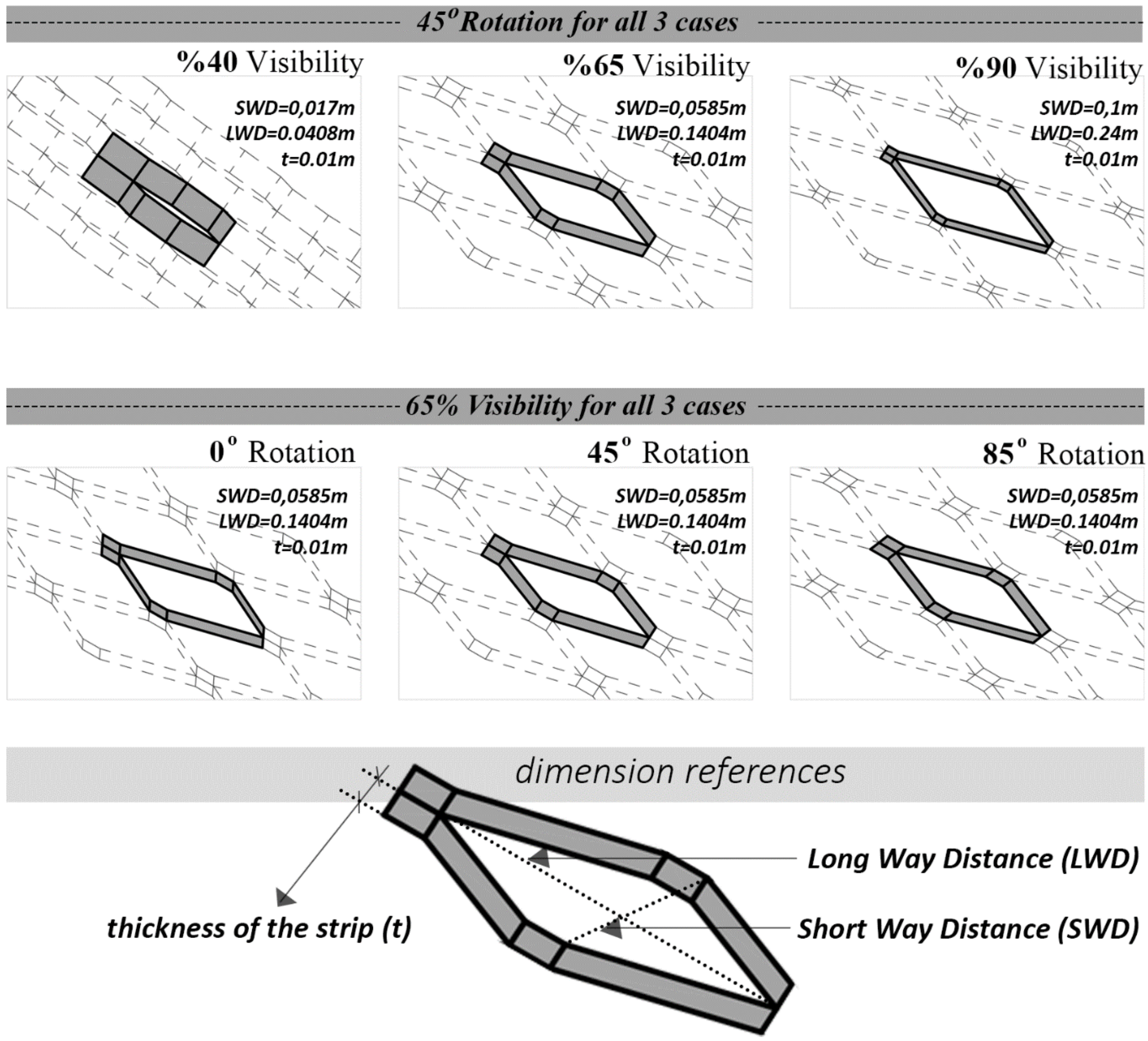


Figure 42: Description of the preliminary analysis simulation configurations, Credits belong to the author

RESULTS: preliminary model analysis

7. Preliminary Model Analysis Results

After finishing all the simulations that are summarized above, each CsDA result that is obtained by results of the simulations, are collected in an excel file in order to be able to compare them with charts.

The result that the simulation is giving to us is the percentage of the defined horizontal surface of the shoebox model, that is in the comfort range for more than %50 of the time. The comfort range is identified within the values for illuminance between 250 lux and 2000 lux, according to the average activities. **Meaning that, as the CsDA**

percentage increases the comfort increases too. Thus, while looking at the results, it is important to comprehend that the changes in the parameters are supposed to increase the CsDA value. This increase would be called as an "improvement" for the rest of the thesis.

Below, the analysed results of the significant configurations are shown in an excel chart. All the results are compared with the configurations where neither with expanded metal mesh or any other shading device, in order to also see the impact of using expanded metal mesh and its significance as shading device for different conditions.

CsDA results [%]		NO EMM	PARAMETERS					
			VISIBILITY PERCENTAGE (45° rotation)			ROTATION OF THE STRIPS (65% visibility)		
			40%	65%	90%	0°	45°	85°
MILANO	NORTH	55.55	40.97	53.47	50.69	51.38	53.47	46.52
	SOUTH	52.08	58.25	55.83	54.86	63.19	55.83	53.47
	EAST	62.5	47.91	57.63	61.11	59.72	57.63	53.47
	WEST	59.02	43.75	54.16	58.33	54.16	54.16	50.69
OSLO	NORTH	50.69	38.19	48.61	47.22	46.52	48.61	43.05
	SOUTH	42.36	49.3	46.52	45.13	52.08	46.52	43.75
	EAST	50.69	41.66	52.08	52.77	54.16	52.08	47.91
	WEST	52.77	40.27	49.3	51.38	49.3	49.3	45.13

Table 2: CsDA results of the preliminary analysis simulations

In order to perceive the improvement that is achieved for the CsDA value, each row, meaning each specific climate and orientation have been considered specifically. The first row is showing the results that given for the cases without the application of EMM. That is why, for the variations of the with EMM configurations; if the CsDA value is exceeding the initial value, they are marked with blue colour. This would show that expanded metal mesh has a positive impact, and it is working for that configuration.

As the results are showing, the most amount of impact observed can be seen for the south façade, which is due to the angle of the sun that is in a higher angle. While for the north façade, the differences are not that high an in a negative way since the solar radiation affecting the indoor environment is not too significant in the first place. The lower values are mostly because of the lower light levels in the deeper areas of the room.

The other crucial comment would be that for the east and west façades, the perpendicular angle of the sun requires a shading device that is placed in the opposite direction. The horizontality of the expanded metal sheet design leads the results to be insignificant. The effect of placing the shading in a horizontal or a vertical way is actually a highly important aspect to be considered.

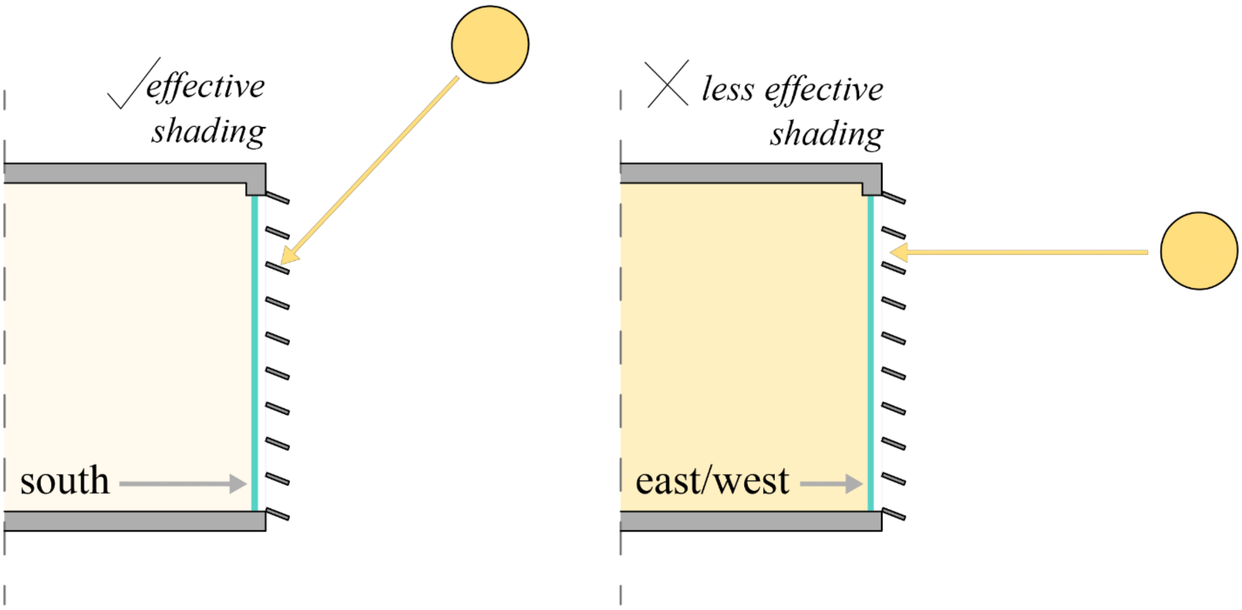


Figure 43: Diagram representing the different impact of EMM on orientations, Credits belong to the author

The objective that is explained is represented with this diagram. The fact that expanded metal mesh places horizontally on a surface is making the south orientation to be much more effective than the east and west façade is described with this exaggerated drawing. Moreover, it is perceivable that the north façade using the metal mesh as a shading device has decreased the CsDA results. **Which is the reason why, it has been decided that going into more in depth analysis with the south façade was essential.**

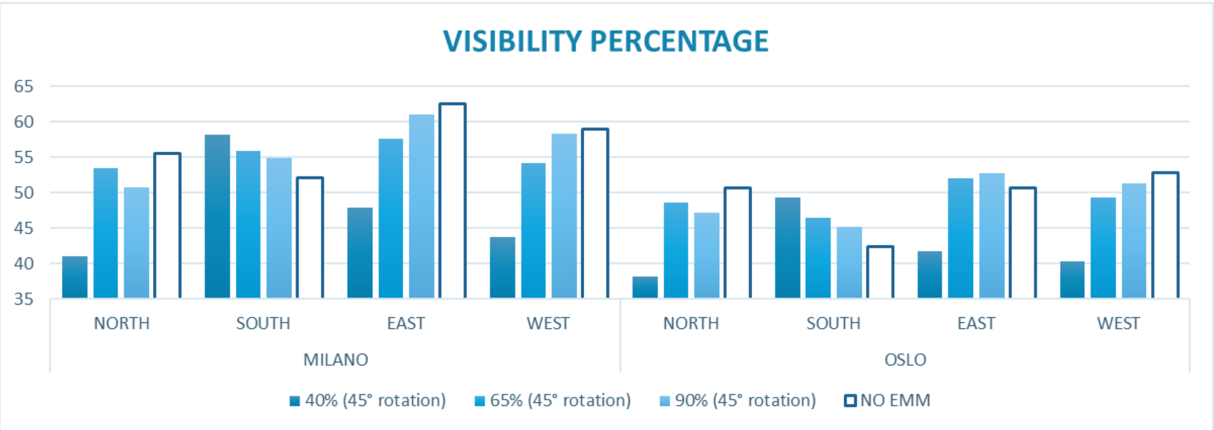


Figure 44: Graph showing the impact of visibility on different configurations

The graph above is showing the changes in each result while varying the visibility percentage parameter. For all these configurations the rotation of the strips has been kept the same to be able to have an isolated idea of this geometrical property. Firstly, it can be stated clearly that most of the configurations are giving worst results compared to the NO EMM variations. This is indicating the fact that the comfort is affected by the under-lit areas so, that even though the areas closer to the glazing are managed to be controlled in a better way, the necessity in the deeper parts are dominating the results. In any case, it can be commented that the higher percentages of visibility are better than the higher ones for the south façade which has the highest amount of solar gains. In fact, the reasonability of the results is showing that the simulations are giving logical outcomes. Moreover, for the south orientation which generally is the most critical one to be observed, there is an increase of CsDA; even without using the optimization methodology, for both of the climates. Moreover; for both of the cases the cases, the configuration which gives the best results are the one with **40% is visibility** (minimum variation value) + **5% of strip rotation angle** (the smallest value that indicates the closest to a flat strip). The reason for that is the expanded metal mesh to work as small sized, repetitive overhangs.

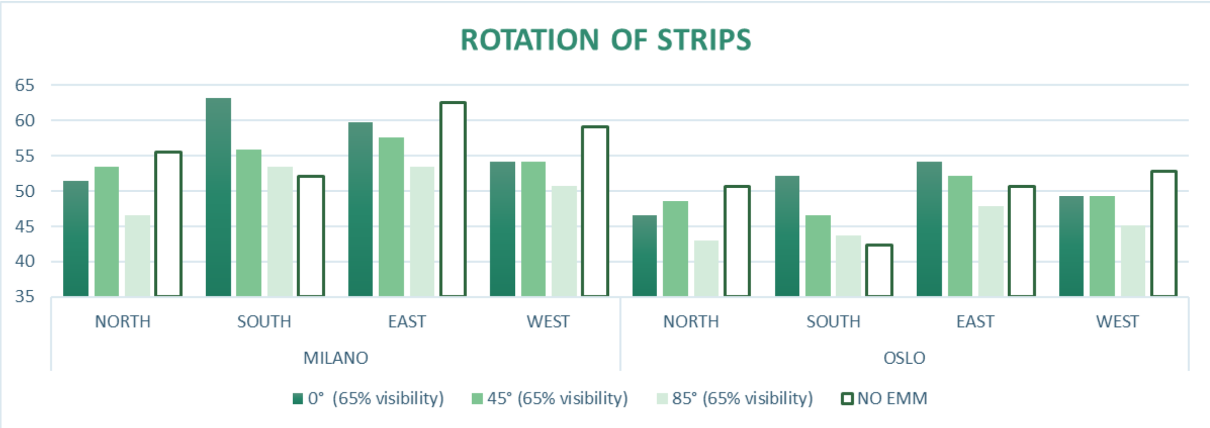


Figure 45: Graph showing the impact of rotation of the strips on different configurations

As predicted before, changing the visibility percentage is giving more significant results than the other parameter since it is defining the amount of solar incident that will enter inside the room. The best results are again given by the south façade and secondly the east façade. Thus, the best value for the customized spatial daylight autonomy is the 5-degree variation that is the one closer to a flat surface. For the west façade, the changes do not have much of an impact due to the horizontal angle of the sun.

As it is stated in the climate definition of these two locations; there is an important difference between their temperature and solar radiation. That is why it is interesting to compare the advantages that can be obtained by the expanded metal mesh and the different reactions of the climate model, within orientation changes. For the orientations where the daily solar gains are higher, the difference between two locations is more significant because of the higher necessity for a shading device. For the north façade, the change is very low since the comfort level is not related to the over-lit areas but the underlit areas.

By this simple CsDA analysis, we got a general idea about how the parameters are working and if the impacts are significant. It can be stated that the comfort levels can be increased a lot for the spaces that are oriented to facades with high solar gains. The results with the pre-set parameters for the south façade have given good results that the optimization process is decided to be done for these configurations.

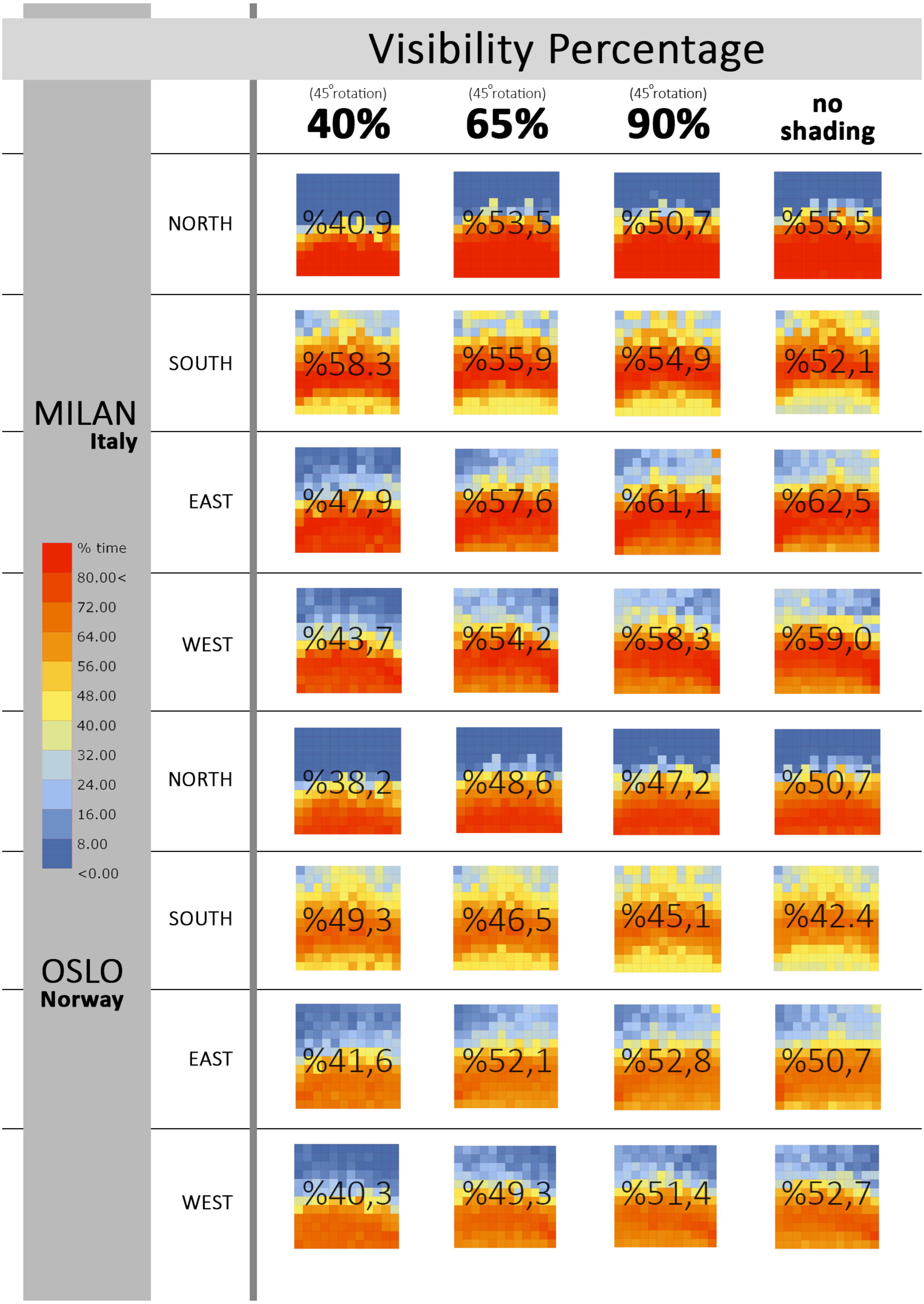


Figure 46: CsDA distribution on the analysis mesh results for visibility percentage

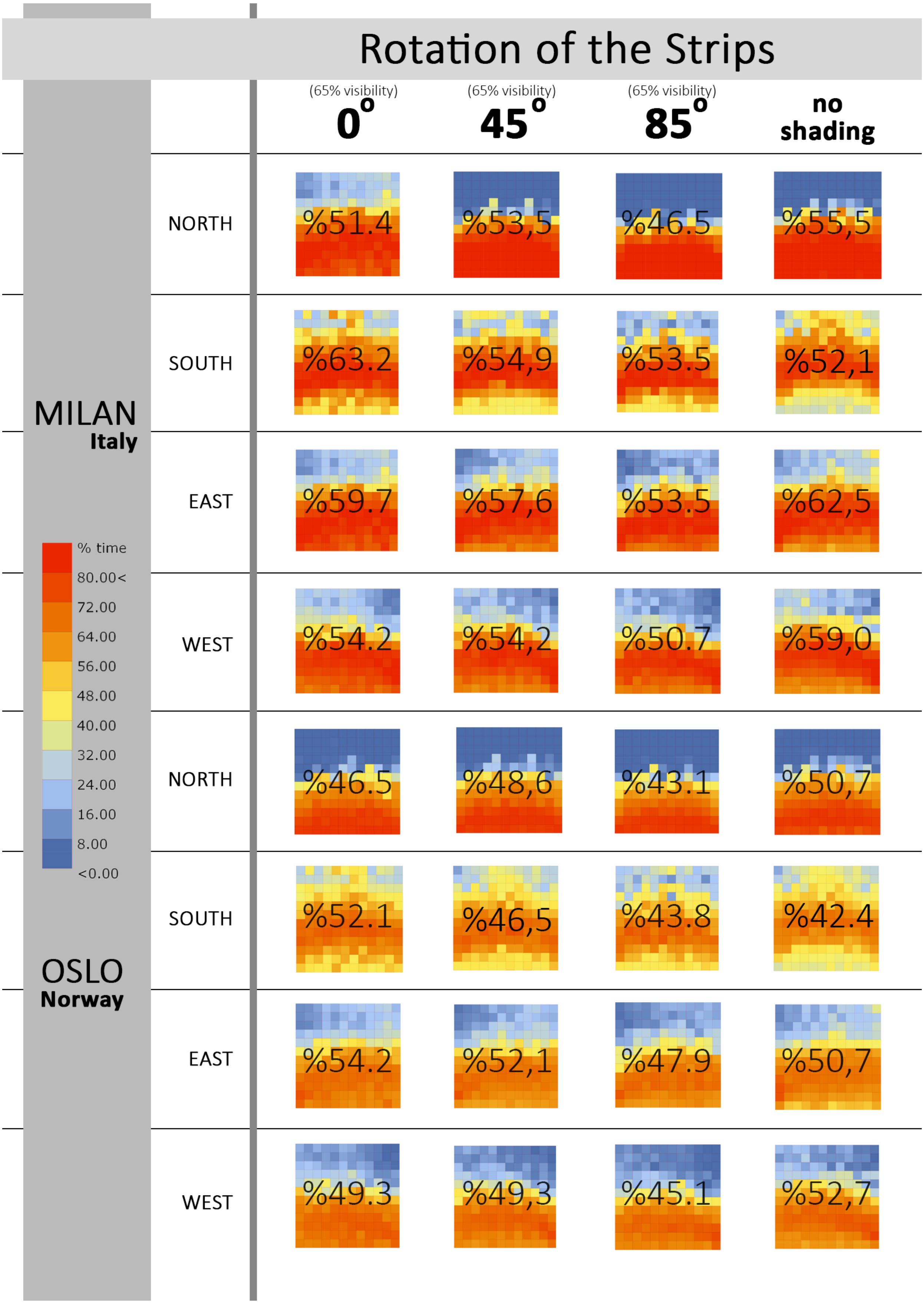


Figure 47: CsDA distribution on the analysis mesh results for rotation of the strips

A

8. *Optimization Results for the Preliminary Model*

After having the first idea of the behaviour of the expanded metal mesh, and its proven that it is working efficiently for the south façade for both of the locations, it was decided to start the optimization process, going into more depth with the south façade.

The optimization is done with Octopus, in the way that is explained in the previous chapter. The genomes are the visibility percentage and the rotation of the strips. It was set up that Octopus would try as many annual daylight simulations as possible in order to maximize (*meaning to increase the indoor daylight comfort*) the customized spatial daylight autonomy value while finding out the best geometrical configuration to do so.

The selected locations were the same as the previous simulations, Oslo and Milano. It is interesting to compare the differences between these two climates because of both their similarities and differences. As their definitions are given in the input definitions chapter; in terms of average temperatures and the solar gains these two capitals are very different, one is defined as cold and the other is warm. However, they are both temperate climates which giving them a common ground to be analysed.

Below the information regarding the outputs of the primary optimization is given in a chart. Moreover, the difference between the CsDA value of the configuration without any shading device and the value of the optimized one is calculated in order to see how effective the optimization methodology is.

CsDA results [%]		NO EMM	PRIMARY OPTIMIZATION			
			OPTIMIZED CsDA	VISIBILITY PERCENTAGE VALUE	ROTATION OF THE STRIPS	**delta**
MILANO	SOUTH	52.08	**70.83**	40	20	18.75
OSLO	SOUTH	42.36	**59.72**	55	10	17.36

Table 3: CsDA results of optimized configurations compared with the no shading configurations

The configuration without any shading device had rather similar results for both of the climates. However, the impact of the optimization is different. For Milano, the CsDA value is managed to be increased 18.75 while for Oslo it is 10.42. The rotation of the strips is 20 degrees and 10 degrees in order. The similarity of this geometrical parameter is due to the orientation that is shout for both of them. Being close to a flat/ horizontal angle, block the solar incidents to come inside the room space and improves the daylight conditions for the over-lit areas close to the glazing. For the visibility percentage value, the values are 40% and 55% in order, which is highly predictable. It was mentioned before that Oslo is colder than Milano hang less solar gains in the buildings. That is why, the necessity for a shading device is less than Milano. While for Milano, there are a lot of time of the year in which the direct solar radiation needs to be prevented in order to avoid over-glared and over-lit areas. Having 40% for the visibility percentage parameter is the proof of this.

Below, the results of the simulation is visually represented with the coloured mesh component in grasshopper so that we can see the impact of the expanded metal mesh in more detail, understanding the differences in different areas of the room. *(The properties of the components used in for the simulation have been explained in the chapter 3.1.)*

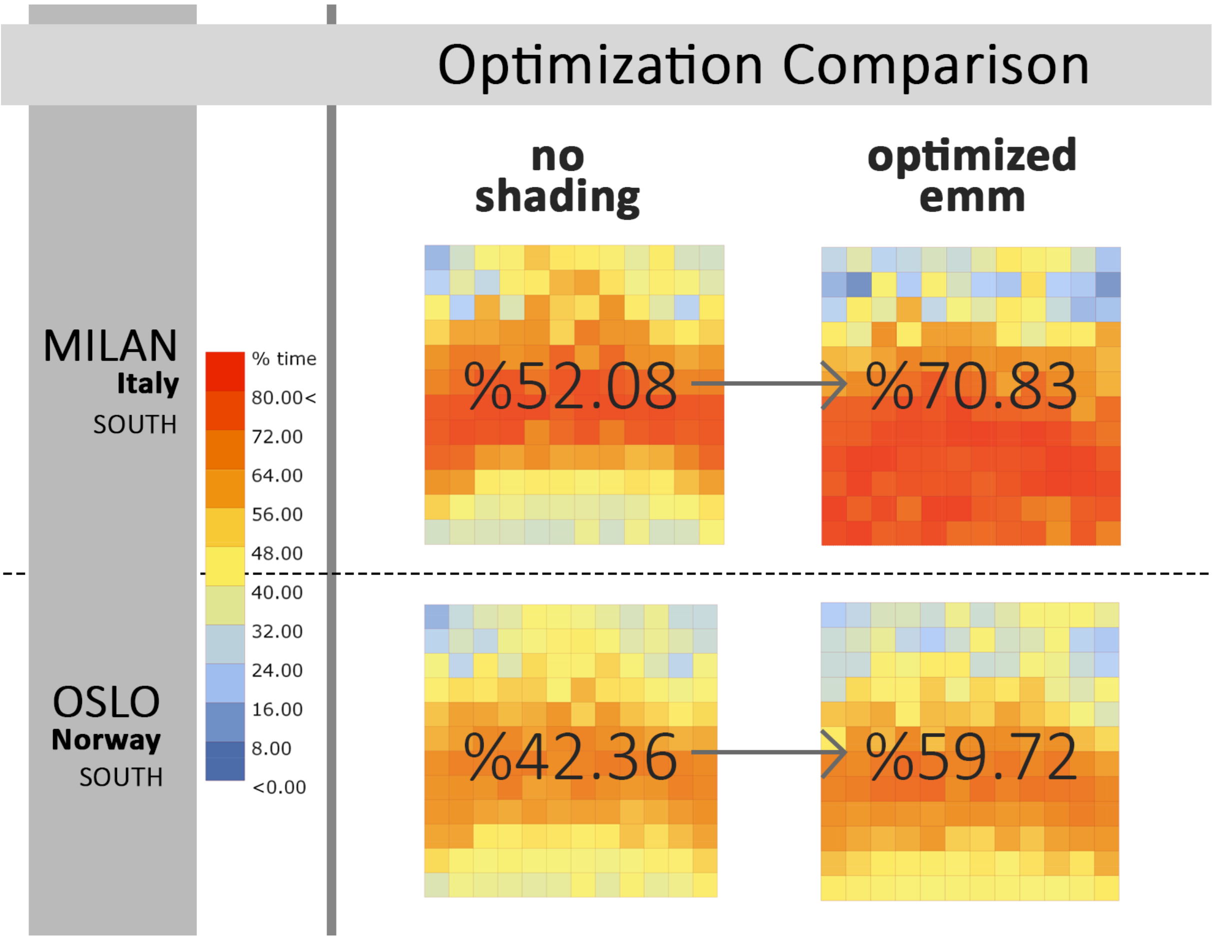


Figure 48: CsDA distribution results of optimized configurations compared with the no shading configurations

Thanks to these graphs it is possible to understand the impact of the shading device in a more detailed way. The optimization for Milano is proven to be working very well since the lower values in the areas closer to the glazing are increased significantly by the help of the shading device. Even though the deeper points of the room is receiving less light which causes the decrease in comfort; the significant increase for the other parts of the room causes the optimization to be efficient. The same approach also applies for Oslo. However, the increase of the daylight comfort is not as much as Milano. This is due to the fact that, the customized spatial daylight autonomy was already less, even in the case without any shading device because of the climate conditions. Even the middle parts that generally have the best values are not as good as Milano. However, the optimized value that is around 60%, is a sufficient value for daylight comfort.

Even though, there is 10% of difference between the optimized values of the climates, the improvement that is obtained is around 11% for both of the cases., meaning that the efficiency of the expanded metal mesh is accurate and logical. It is also important to realize the differences of the geometrical parameters that are helping to obtain these results.

Below, the visualizations of the geometrical parameters are represented in order to show the translations of the optimized values to the geometry. The differences will give an idea about the adaptation of the shading device to different climates.

The first one is the values for Milano. The visibility percentage is the lowest possible that is 40%. However, the fact the rotation of the strip is 10 degree meaning that it is almost flat; increases the visibility of the façade to much higher levels. (since the visibility is calculated and simplified according to the worst possible conditions)

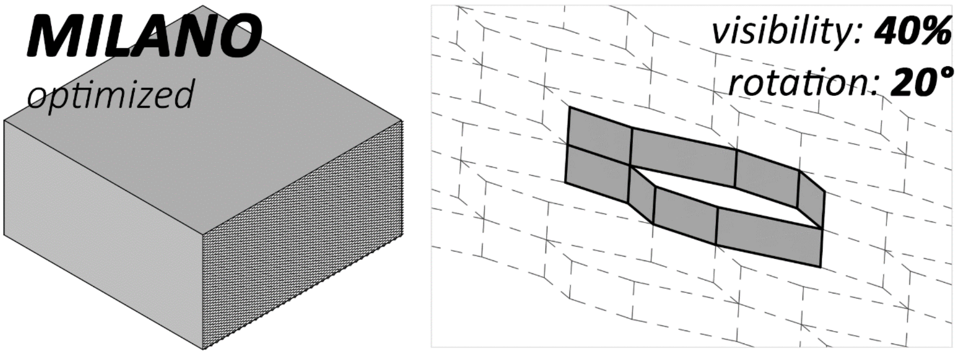


Figure 49: Diagram describing the optimized parameters of Milano shoebox case

The second one is the values for Oslo. As it is clear from the images, the angle of the strips is highly similar with the Milano case. This is due to the fact that both of them are oriented in the south façade and that the angle of the sun is very high for both of the cases. While the visibility is 15% more than Milano, which is due the colder climate.

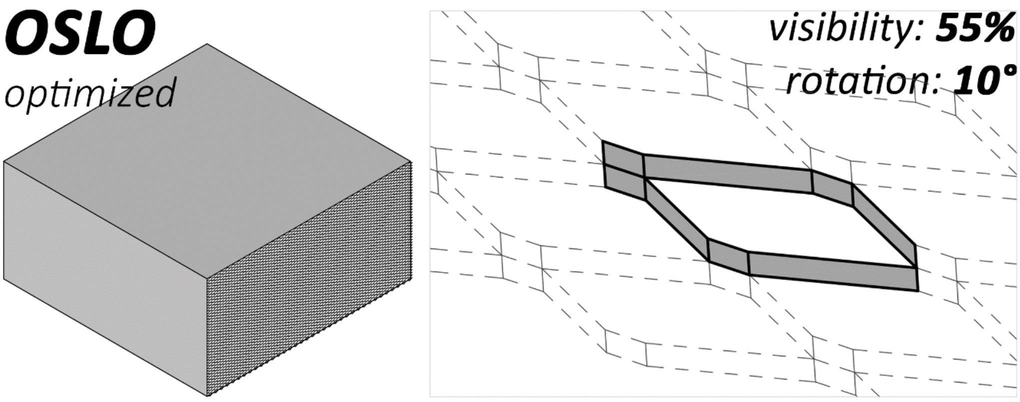


Figure 50: Diagram describing the optimized parameters of Oslo shoebox case

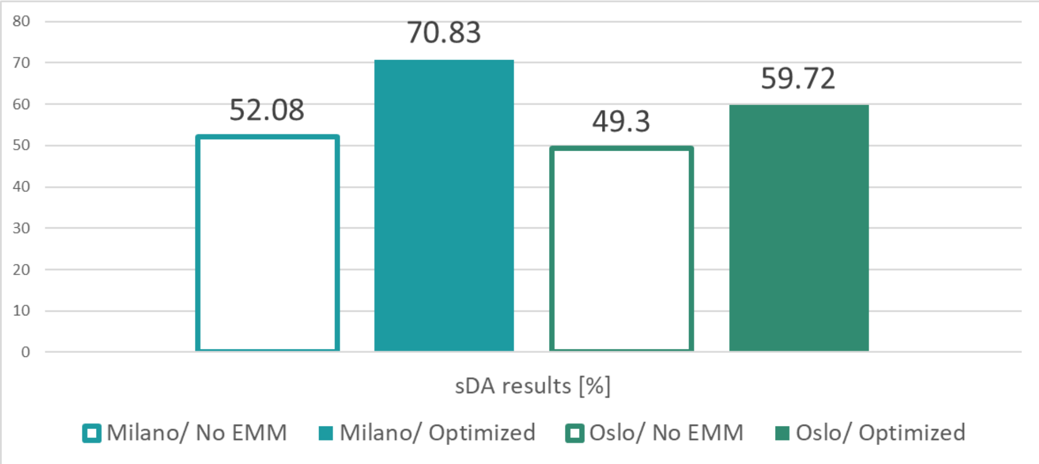


Figure 51: Graph comparing the optimization results of preliminary analysis simulations

Above, there is a summary of all the values obtained in one graph to show the differences in a better way. The best value achieved is 70.83% which is a quite high value considering that the thresholds of the simulations are very limited.

METHODOLOGY

9. *Case Study Analysis*

The second part of the optimization process is the case study analysis. The shoebox model gave an approximate opinion about the efficiency of the expanded metal mesh as a shading device. However, it is also very useful to analyse the case study building and understand if the system is working with real cases where the function, illuminance thresholds, space size and the surfaces are defined by engineers and architects or the specific location and climate.

9.1. Description of the Case Study Buildings

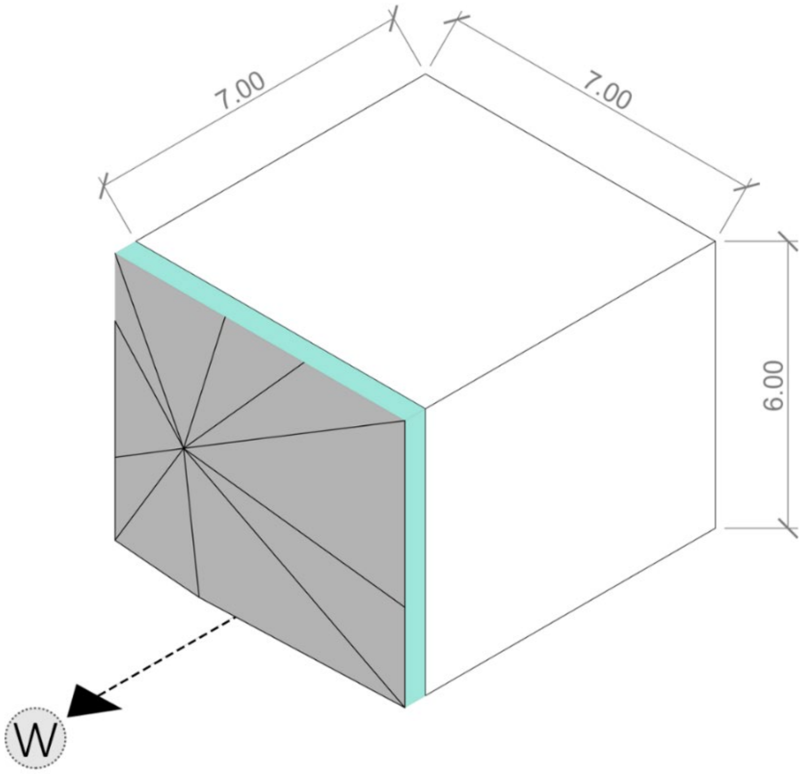
The first of the case study process is to find, understand and explain the significant building where the expanded metal mesh is used as a exterior cladding. The objectives of the process where these examples are found were, to find different types of climates and functions, make sure that the expanded metal mesh is applied also for shading purposes (not only aesthetical reasons) and that there are enough technical information about the building in order that the subjected space can be modelled precisely to have logical and realistic results.

In the next chapter the case study buildings will be explained in detailed. Moreover, the selected space to be analysed and its properties would be described in detail. There are five buildings which have very interesting façade typologies in terms of their surface qualities and ways of using the expanded metal mesh.

9.1.1. HOUSTON DYNAMO BBVA COMPASS STADIUM, HOUSTON

Figure 52: BBVA Compass Stadium Pictures, Image Credits: https://www.designboom.com/architecture/populous-bbva-compass-stadium-houston

The 'BBVA compass stadium' is intended to be a focal point in Houston's east downtown redevelopment plan. As a result, the structure, designed by populous, was envisioned with a visually dynamic and distinctive form creating by a continuous tessellated exterior. **This triangulated patterning is composed primarily of permeable expanded metal screens,** with bright orange accent pieces sympathetic to the colour scheme of its home team, the Houston dynamo. the building contains 22,000 seats and is primarily used for soccer matches but also accommodates lacrosse, rugby, and concerts. located in a developing part of the city, the stadium is easily accessible for a growing community of fans. the venue serves to support the growth in popularity of soccer culture and industry in the US. [7]



Function:

SPORTS/STADIUM

Illuminance threshold:

300-1500 lux

Floor area: **49 m^2**

Emm surface type:

Triangulated

Figure 53: Model description of the BBVA Compass Stadium, Credits belong to the author

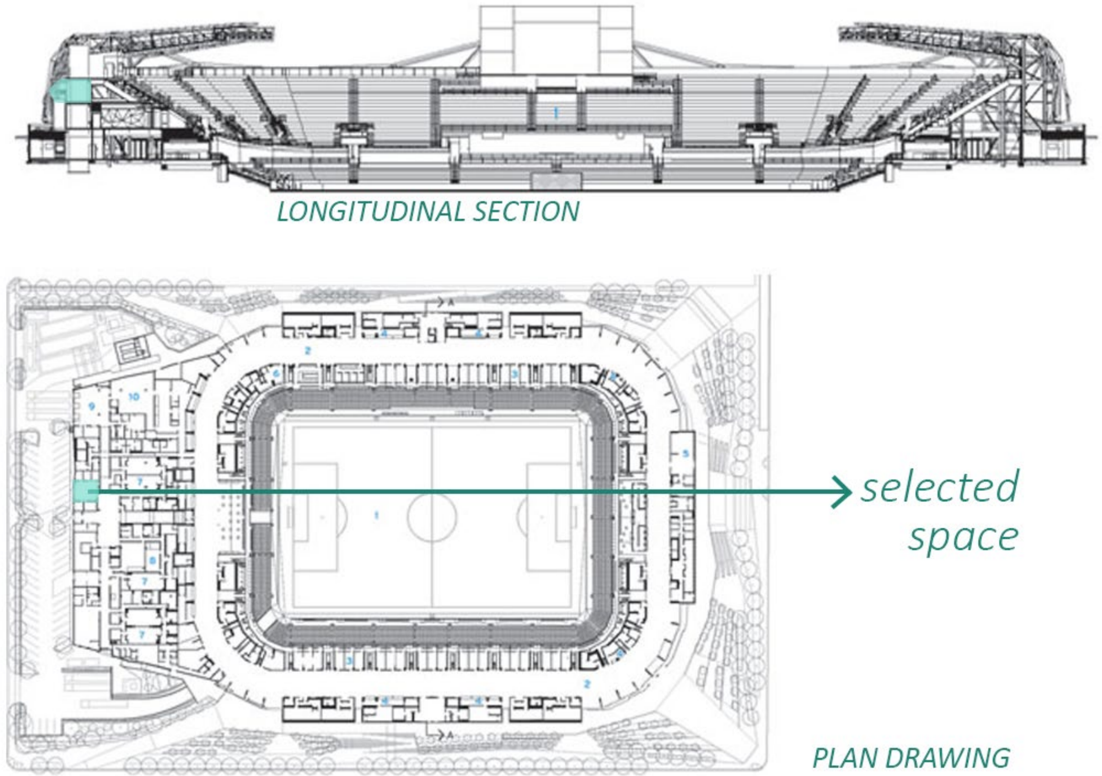
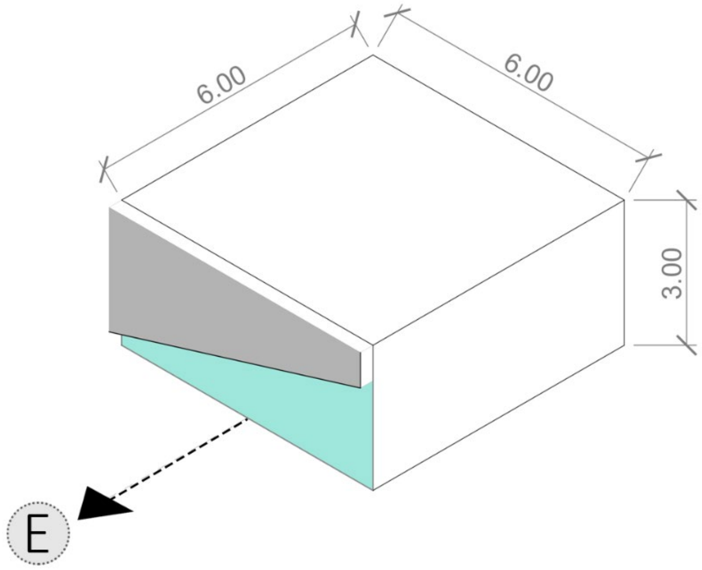


Figure 54: 2D drawings of BBVA Compass Stadium highlighting the selected analysis space, Credits: Credits: https://www.designboom.com/architecture/populous-bbva-compass-stadium-houston

9.1.2. THE PREMONT LANTERN, QUEBEC

Figure 55: The Premont Lantern Pictures, Photo Credits: https://www.arch2o.com/the-pr%C3%A9mont-lantern-dmg-architecture-bourgeois-lechasseur-architectes/

The Prémont Harley-Davidson is located in Québec. The complex measures nearly 8000 square metres and houses a large showroom, a museum that includes several collectors' items, and a large repair shop. The program also includes a theme restaurant and administrative offices. The architectural part consisted of creating an iconic building, a landmark in the countryside. On the southern end of the site, the building culminates in a truncated tower, the upper part of which disappears in order to make room for the Prémont lantern which can now be seen at night like a lighthouse—a landmark visible from the highway and surrounding areas. [47]



Function:

GALLERY/MUSEUM

Illuminance threshold:

700-2500 lux

Floor area: **36 m^2**

Emm surface type:

Flat/cutted

Figure 56: Model description The Premont Lantern, Credits belong to the author

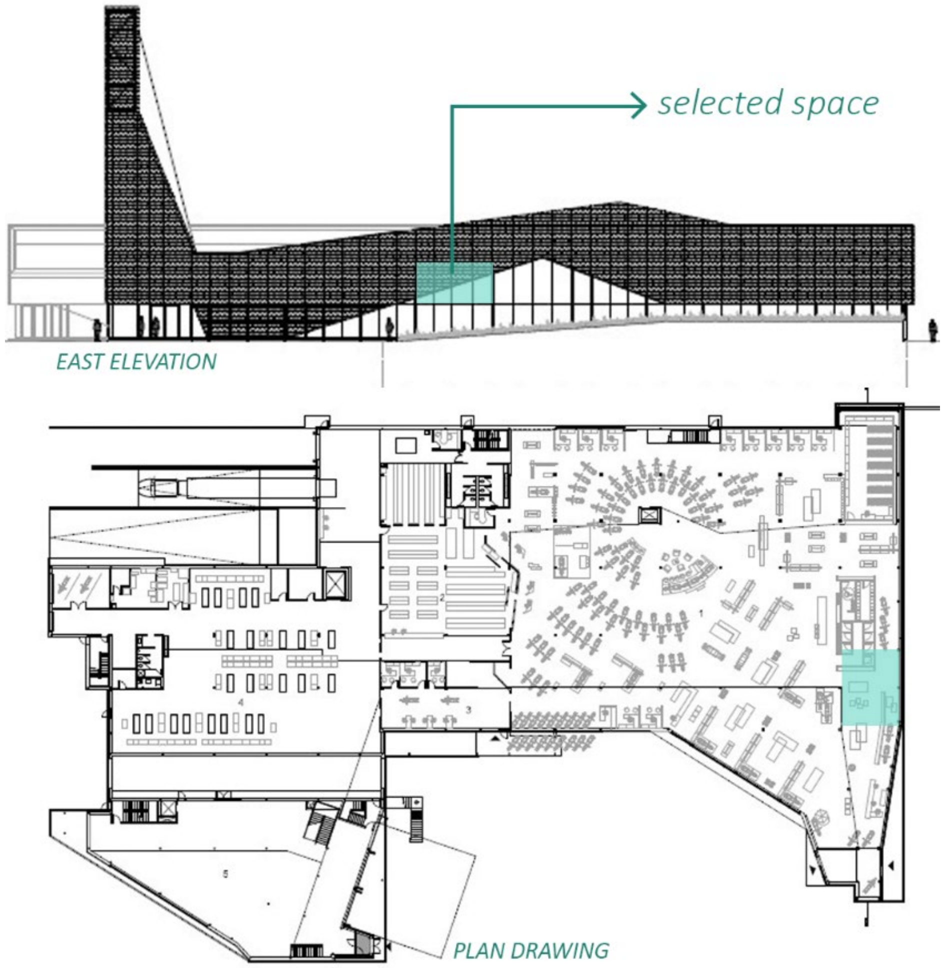
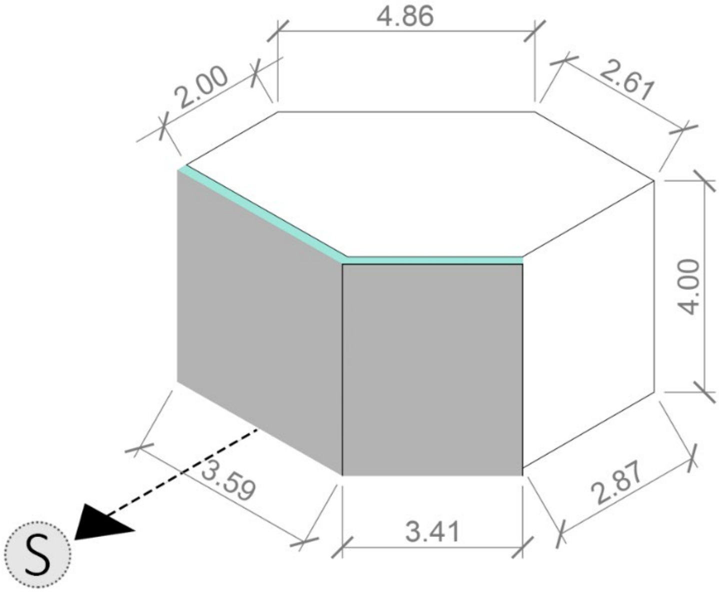


Figure 57: 2D drawings of The Premont Lantern, Photo Credits: https://www.arch2o.com/the-pr%C3%A9mont-lantern-dmg-architecture-bourgeois-lechasseur-architectes/

9.1.3. THE YOUNG VIC THEATER, LONDON

The main difference of the selected space compared to the other is that the plan shape of it is not a rectangle as the others. It has an irregular shape where 2 triangle pieces are cutted of. Moreover, the space is in the corner so the façade is glazed from two different surfaces of the space, which makes the room also take daylight from the west façade; which is why it would be an interesting comparison.



Function: **THEATER/ ART CENTER**

Illuminance threshold: **500-2000 lux**

Floor area: **20,16 m^2**

Emm surface type: **Joined surface**

Figure 58: Model description of the Young Vic Theatre, Credits belong to the author

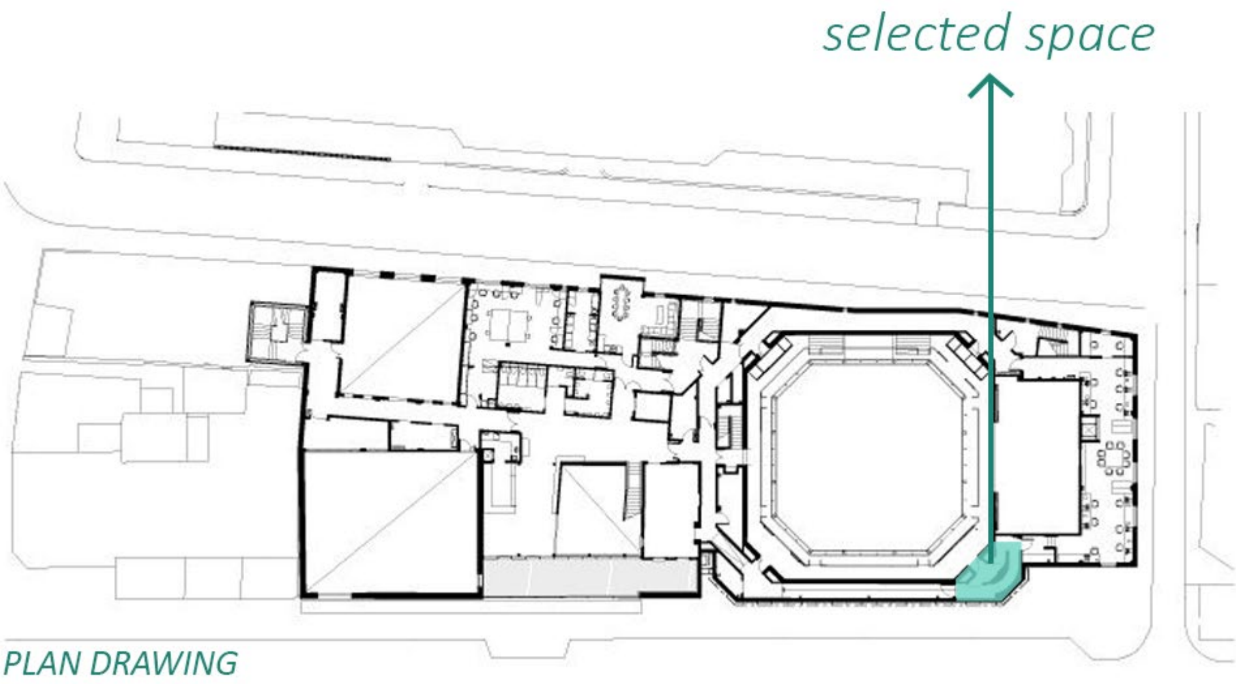


Figure 59: 2D drawings of The Young Vic Theatre highlighting the selected room for analysis, Credits: http://haworthtompkins.com/work/young-vic#:~:text=Young%20Vic%20-%20Haworth%20Tompkins

9.1.4. MAISON FOLIE DE WAZEMMES, LILLE, FRANCE

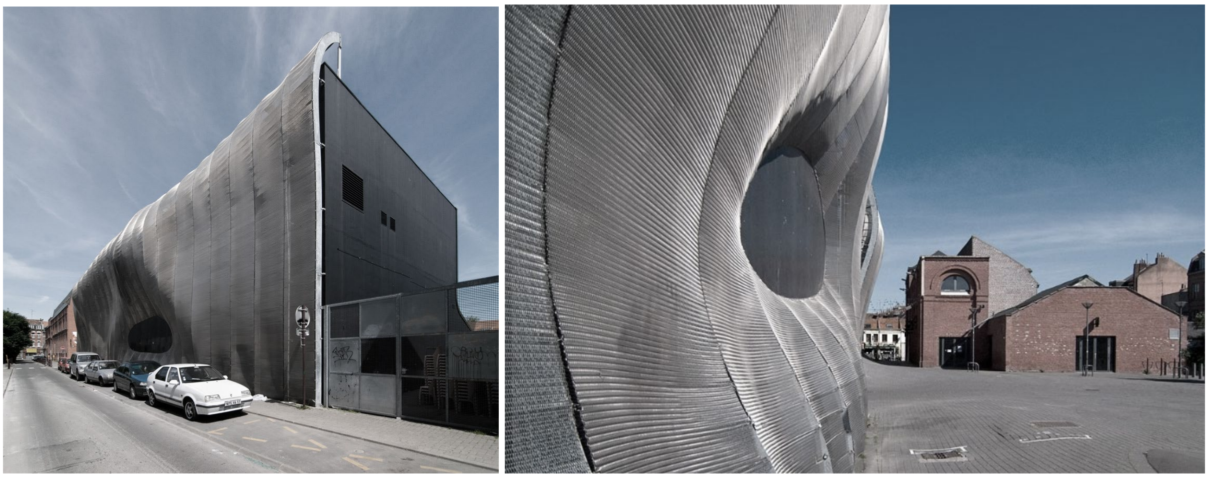
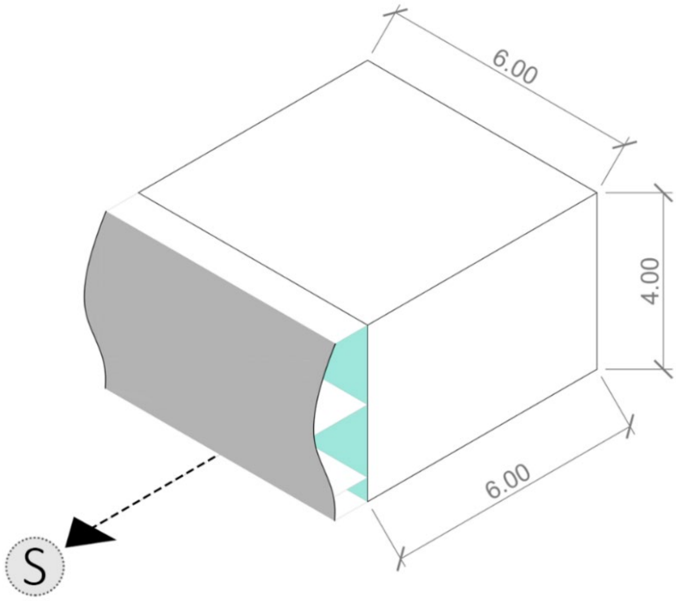


Figure 60: Maison Folie de Wasemmez pictures, Image credits: http://architettura.it/architetture/20040330/index.htm

The Maison Folie de Wazemmes that is located in Lille, France project has won the competition of Cultural Capital of Europe in 2004 and got the first price. The functions of the project include; multipurpose hall, studios and exhibition spaces, media library, day-care, artists' communal space, offices, and soup restaurant. A complex of buildings that consists of the renovation of an old textile factory into a conglomerate of art-related functions plus a newly constructed multi-purpose hall, that is used for concerts, theatre productions, fashion shows and the like. As in Rotterdam, Hamburg or Glasgow art moves into disused industrial buildings to transform and revive the identity of a city. [9] The adaptation of the expanded metal mesh to the simplified model of this case-study building was different than the other ones due to the curved surface. The mesh is adapted in such a way that the parametric modules of the mesh is oriented on the surface grid points according to the normal vectors. The rotation of the mesh is the same for each point of the surface in order to have a convenient comparison of the parameters. The procedure is explained in a clear way in the chapter 11.1.



<u>Function:</u> **STUDIO/ EXHIBITION**

<u>Illuminance threshold:</u> **500-2000 lux**

<u>Floor area:</u> **36 m^2**

<u>Emm surface type:</u> **Single Degree Curved**

Figure 61: Model description of Maison Folie de Wasemmez, Credits belong to the author

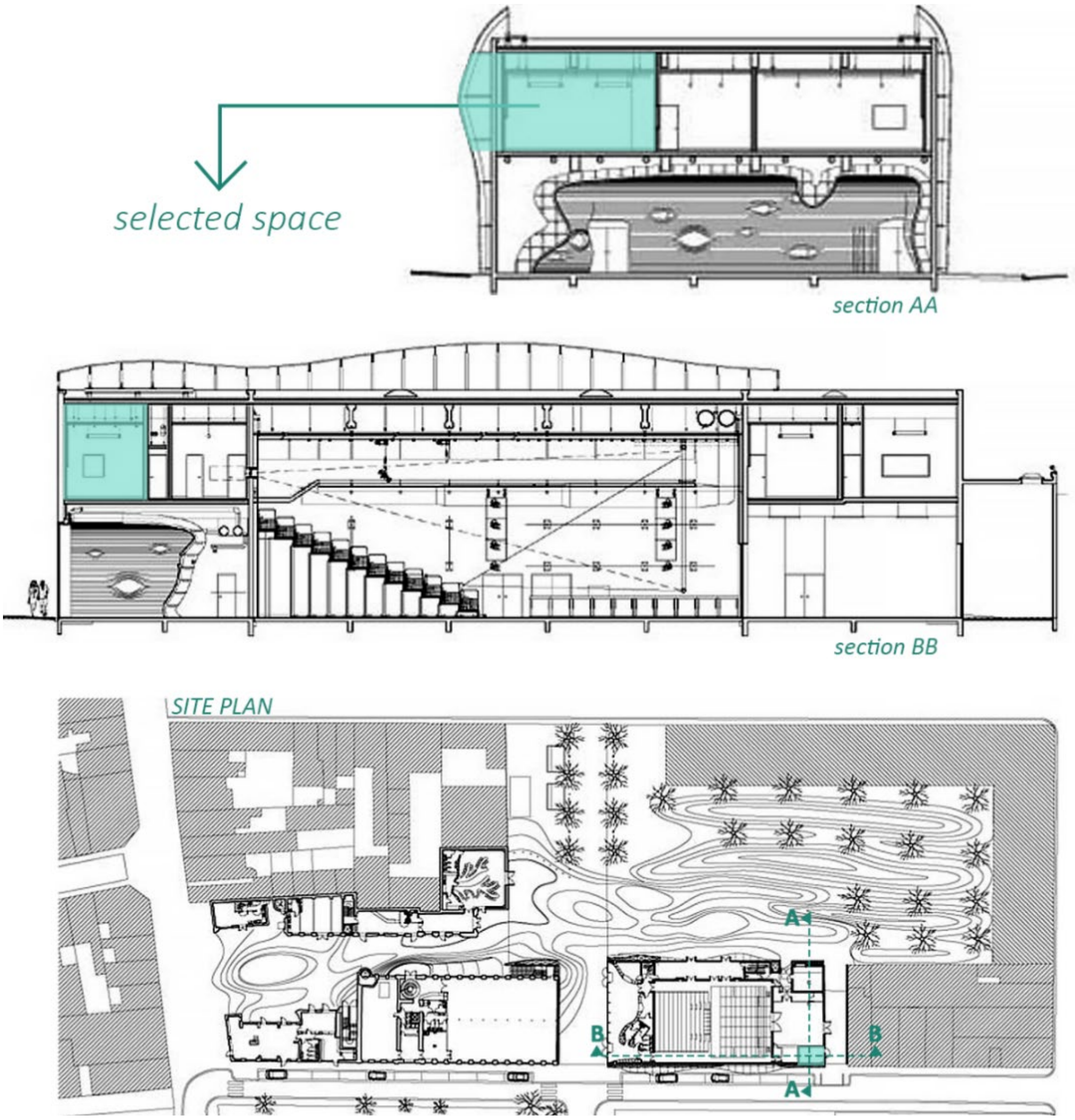


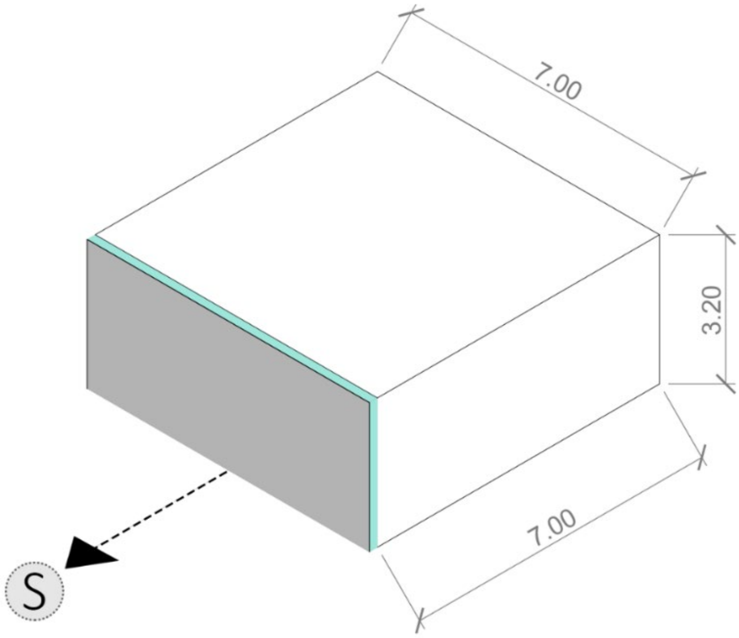
Figure 62: 2D drawing of Maison Folie Wasemmez, highlighting the location of the selected space to analyse, Credits: https://www.archiweb.cz/en/b/maison-folie-de-wazemmes

9.1.5. MUSEUM OF CONTEPORARY ART, NEWYORK

The New Museum is clad in a seamless, anodized expanded aluminum mesh chosen by SANAA to emphasize the volumes of the boxes while dressing the whole of the building with a delicate, filmy, softly shimmering skin. With windows just visible behind this porous scrim-like surface (*achieved with a common material never before employed to clad major building façades*), the building appears as a single, coherent and even heroic form that is nevertheless mutable, dynamic, and animated by the changing light of day—an appropriate visual metaphor for the openness of the New Museum and the ever-changing nature of contemporary art. [15]

Figure 63: Photos of New York Contemporary Museum of Art, Photo Credits: https://www.dezeen.com/2007/11/22/new-museum-of-contemporary-art-in-new-york-by-kazuyo-sejima-ryue-nishizawasanaa/

The windows are just behind this mesh, which makes the set has a unique appearance, which changes with daylight. The striking exterior differs markedly from neutral interior. With the exception of an interior elevator and bright electric green cherry mosaics in rooms low level, the museum presents polished Gray concrete floors and white walls, as well as structural members exposed diagonal. A floating screen softens long roof visible features, filtering light from a fluorescent tube trellis. Ducts, sprinklers, and fire-proof material are also visible.



Function: **MUSEUM/ GALLERY**

Illuminance threshold: **1000-2500 lux**

Floor area: **49 m^2**

Emm surface type: **Flat**

Figure 64: Model description of the Contemporary Art Museum , Credits belong to the author

The selected space is one of the gallery spaces where it is connected with the office spaces. This model is probably the one that is the most similar to the showbox model, both in terms of the size of the room as well as how the expanded metal sheet is applied that is on a simple flat surface. However, the building concept and how spaces are connected is the most interesting qualities of the design.

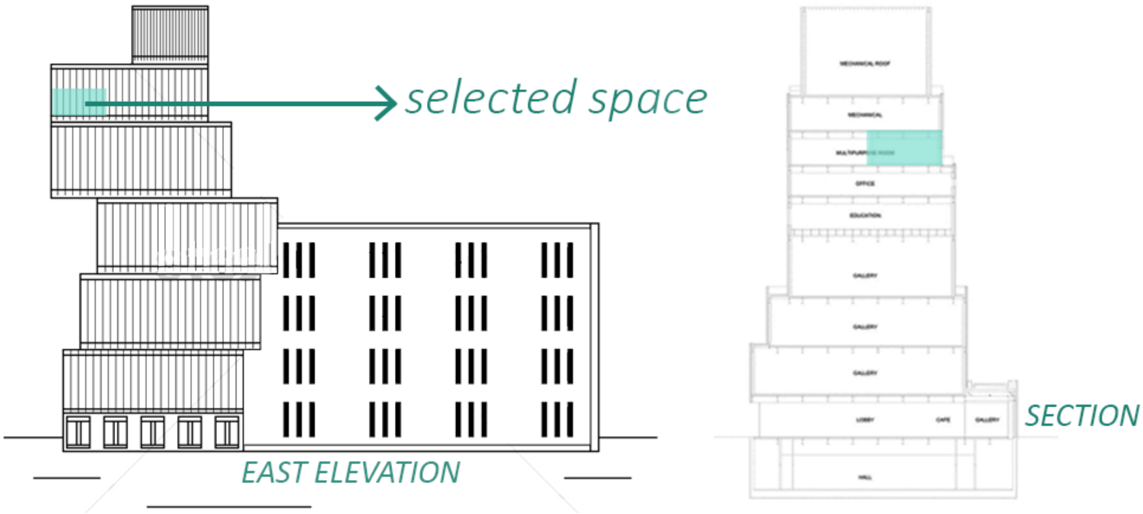


Figure 65: 2D drawing of Contemporary Art Museum highlighting the selected room for analysis, Credits: https://www.archdaily.com/70822/new-art-museum-sanaa

9.2. Case Study Optimization

In the previous chapter, the case study buildings and the simulation models selected from them are described in a detailed way. The aim of this process is to optimize the expanded metal mesh properties of each of them. Even though these building are already using this material, it is aimed to improve the daylight performance of them by this research's optimization methodology with octopus. This achievement would be proven by the comparison of the optimized results with the result which are obtained with the same model without using any expanded metal mesh. This way, the application in real life structures would be proved to be efficient in terms of daylight performance, for 5 different climates and building types.

The first thing that is done after modelling each space in Rhino was to introduce the surfaces in Grasshopper as components. Basically, there are 3 different types of surfaces for the model. First, the components including the walls, the glazing surface and the floors are joined and introduced as the "box model" which defined the closed boundaries of the room. Then the glazing surface is introduced again as a single surface to be used for Honeybee zone. As the last step, the shading should be introduced. However, the shading model that is created in a parametric way controlling the geometrical parameters, has already been created in grasshopper. That is why, the multi-surfaced brep obtained by this shading script and the additional surfaces that are also modelled in rhino (the connection surfaces between the glazing surface and shading system) are joined and defined as the final shading component. This way, the Honeybee Zone is prepared, where the simulation mesh is the same floor that is elevated 0.750 meters from the 0 level and divided into the test points on which the size of the grid is 0.5 meters, as the previous shoebox models.

The next step is to prepare each model for the optimization process. Since each of them has different functions and different values for the thresholds of the illuminance ranges; the simulations needed to be done step by step. The comparison output is again the customized spatial daylight autonomy. (so that the measurement method is the same with all the previous simulations) That is why, the script that is used for the simulations is the same as the simple shoebox analysis, the input model is the only difference between them.

As mentioned before, the purpose of these simulations is to compare the optimized results with the "no EMM" configurations' results. Thus, the simulations without the shading system is made for each configuration. After that, the optimization process had been started. Before moving on to Octopus, a single manual simulation should be made to be able to start the process where Octopus tries different parameters to find the maximum result for CsDA. Then the geometrical parameters (visibility percentage and the rotation of the strips) are connected to octopus as genomes, and the customized spatial daylight autonomy result value is connected to octopus as the fitness. After defining the locations and the illuminance ranges are defined within the EPW file and the number sliders; the optimization is started. Since the surfaces of the case study building are more complex than the simplified shoebox model; the simulation time became longer. That is why, instead of running the simulations for 15 hours, 20 hours have been decided to be dedicated for each optimization process in order to find the best version of each configuration. After the 20 hours of optimization is done for each case study model, the manual simulation is done one last time with the point in octopus that is indicating the maximum value of customized spatial daylight autonomy; so that; the geometrical parameters that are achieving this goal is noted. Each result is collected in an excel file to have the final results all together and comparable. While the grid visuals that show the comfort distributions in the whole room are also printed along the process.

In the chart below, the configuration properties of each case study building are given in a summarized way. The differences of the; location, orientation, floor area, depth of the room, height of the room, function and the illuminance thresholds are identified in a clear way so that the understanding phase of the result would be clearer.

	CONFIGURATION PROPERTIES						
	LOCATION	ORIENTATION	FLOOR AREA [m^2]	DEPTH OF THE ROOM [m]	HEIGHT OF THE ROOM [m]	FUNCTION	ILLUMINANCE THRESHOLD [lux]
BBVA COMPASS STADIUM	Houston, USA **(29.749907, -95.358421)**	WEST	49	7	6	Sports/ Stadium	300-1500
THE PREMONT LANTERN	Quebec, Canada **(46.829853, -71.254028)**	EAST	36	6	3	Gallery/ Museum	700-2500
THE YOUNG VIC THEATER	London, England **(51.509865, -0.118092)**	SOUTH	20.16	4.9	4	Theater/ Art Center	500-2000
MAISON FOLIE DE WAZEMES	Lille, France **(50.629250, 3.057256)**	SOUTH	36	6	4	Studio/ Exhibition	500-2000
MUSEUM OF CONTEMPORARY ART	New York, USA **(40.730610, -73.935242)**	SOUTH	49	7	3.2	Gallery/ Museum	700-2500

Table 4: Excel chart defining the characteristic of the case study configurations

As mentioned before the illuminance thresholds are approximately defined according to the standards obtained by “engineering toolbox” website. Since almost all the defined functions are different than each other; the illuminance threshold is different. That is why, before initializing each simulations the inputs needed to be checked and changed according to the requirements.

Another important and significant difference was the orientation which is not defined as “south façade” for two of the cases. It has been confirmed before that the most significant impact that we can get with the application of expanded metal mesh was for the south façade. However, for the analysis of the case studies it was important to confirm the efficiency of the material within their context. That if why the “north vector” in the script definition is changed for each configuration.

Moreover, the changes in the size of the model would have a compelling difference for the results due to the fact that the glazing size changed as well. However, it is very interesting to see the results and prove that the shading system can work also with the higher values of solar gains.

RESULTS: case study analysis

10. Case-Study Optimization Results

Here is the chart were all the simulations results are noted with the geometrical parameter definitions. The difference between the optimized CsDA and he no shading CsDA is calculated in order to obtain the improvements.

An overall comment within the first look at the chart would be that; except for the BBVA Compass Stadium and the New York Museum of Contemporary Art, the results and the improvements with the expanded metal mesh are similar to the ones of the shoebox model. In any case, a variety of different values for the visibility percentage is observed, proportioned to the climatic conditions. Moreover, the changes in the rotation of the strips is again, depending on the orientation of the model, as explained, and understood in the previous chapter.

	NO SHADING CsDA	OPTIMIZED CsDA	VISIBILITY PERCENTAGE	ROTATION OF THE STRIPS	IMPROVEMENT
CASE STUDY OPTIMIZATION					
BBVA COMPASS STADIUM	40.81	**84.95**	*45*	*50*	*44.14*
THE PREMONT LANTERN	16.42	**28.78**	*65*	*30*	*12.36*
THE YOUNG VIC THEATER	34.39	**49.27**	*75*	*30*	*14.88*
MAISON FOLIE DE WAZEMES	24.94	**34.02**	*70*	*30*	*9.08*
MUSEUM OF CONTEMPORARY ART	27.55	**29.08**	*90*	*10*	*1.53*

Table 5: CsDA results comparison of the case study optimizations, indicating the parameter values and the improvements

10.1.1. BBVA COMPASS STADIUM

The first results that is capturing the attention is the **BBVA Compass Stadium** that has the highest CsDA value as well as the highest improvement, even though it has the illuminance thresholds that are the most limited. (300-1500) This is due to the fact that the glazing size of the model is the biggest among all. This way, the problem of underlit areas have been eliminated since the solar gains would be quite high. While for the over-lit areas that causes the initial result without the expanded metal mesh to be 40.81, have been controlled in a very efficient way by adding the shading system. Moreover, the climatic condition of Houston is also helping the values to be higher even if the building is oriented through west façade. The fact that it is receiving the sunlight in a very perpendicular direct angle, is controlled by the visibility percentage value that is the almost the lowest possible; 45%. This is also a predictable result since it has already been explained that the most benefits of the material's behaviour are advantageous for the south façade. That is why, lower values of visibility percentage are necessary to have sufficient levels of daylight comfort inside. While for the rotation of the strips; the degree of angle is 50 that is the closest value to a diagonal variation, which is also an effect of the orientation to be the west façade. Having a flat angle which is the best angle for south façade, does not work for the perpendicular angles, due to the fact that it cannot avoid the direct sun light. The other reason why that this case study has the best results is because of the angles of the surfaces which are pulled by a control point, leading the façade to have day light from many different angles. This way, for every hour of the day, there is a certain amount of solar gains that are transmitted to the modelled space, increasing the average value of comfort.

	NO SHADING CsDA	OPTIMIZED CsDA	VISIBILITY PERCENTAGE	ROTATION OF THE STRIPS	IMPROVEMENT
BBVA COMPASS STADIUM	40.81	**84.95**	*45*	*50*	*44.14*

Table 6: Optimization results for the BBVA Compass Stadium

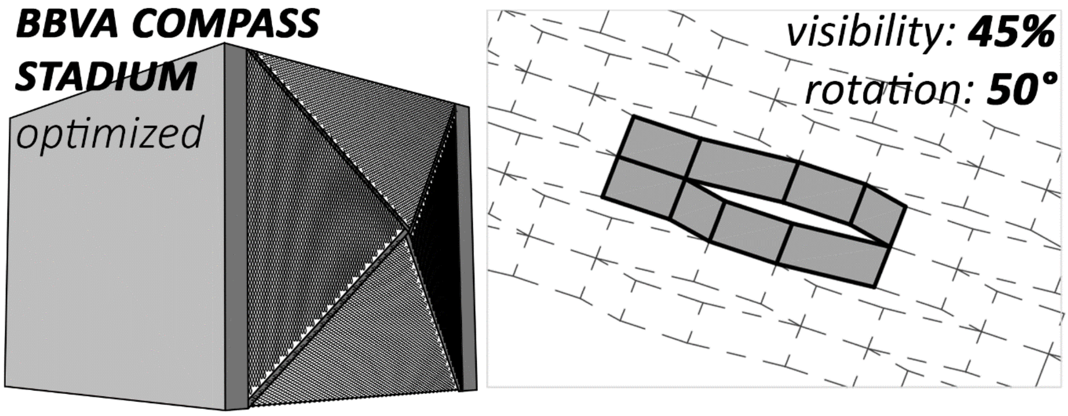


Figure 66: Diagram representing the geometrical parameter values for the BBVA Compass Stadium, Credits belong to the author

10.1.2. THE PREMONT LANTERN

Similar impacts can be observed for **The Premont Lantern** that is oriented towards the east façade. However, the optimized parameter results are quite different from the Stadium. The main reason for that is the climate differences, that is much colder than Houston. Because of this reason, the optimized CsDA value are much lower. Moreover, since the expanded metal mesh is applied on half of the surface of the glazing, the control of the daylight is also less. Not only the application area of the shading system, but also the floor height to be less than the other case study models, leads the results to be less than the others. However, by using 65% of visibility it was managed to increase the comfort to 28.78 from 16.42, while having a 30 degree of angle for the rotation of the strips. In order to increase the indoor comfort, it is necessary to use artificial lightings for this building due to the fact that the lower values are more dependent on the under-lit areas that is caused by the climate conditions. In any case, it is clear that for the hitter days on which the sun light is coming directly to the façade, the comfort is increased by the expanded metal mesh with its shading effect

	NO SHADING CsDA	**OPTIMIZED CsDA**	VISIBILITY PERCENTAGE	ROTATION OF THE STRIPS	IMPROVEMENT
THE PREMONT LANTERN	16.42	**28.78**	*65*	*30*	*12.36*

Table 7: Optimization results for the Premont Lantern

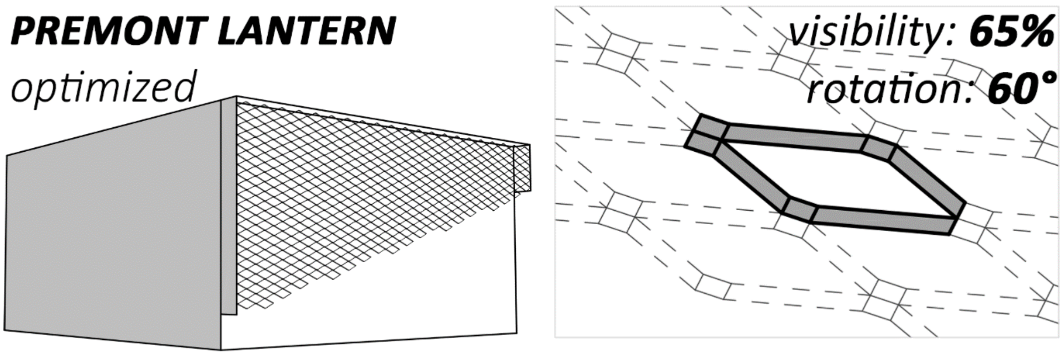


Figure 67: Diagram representing the geometrical parameter values for the Premont Lantern, Credits belong to the author

10.1.3. THE YOUNG VIC THEATER

The other case studies are all oriented to the south façade which is giving them a common ground to be compared. However, due to their different properties, functions, and illuminance thresholds, they are giving much different results.

	NO SHADING CsDA	OPTIMIZED CsDA	VISIBILITY PERCENTAGE	ROTATION OF THE STRIPS	IMPROVEMENT
THE YOUNG VIC THEATER	34.39	**49.27**	*75*	*30*	*14.88*

Table 8: Optimization results for the Young Vic Theatre

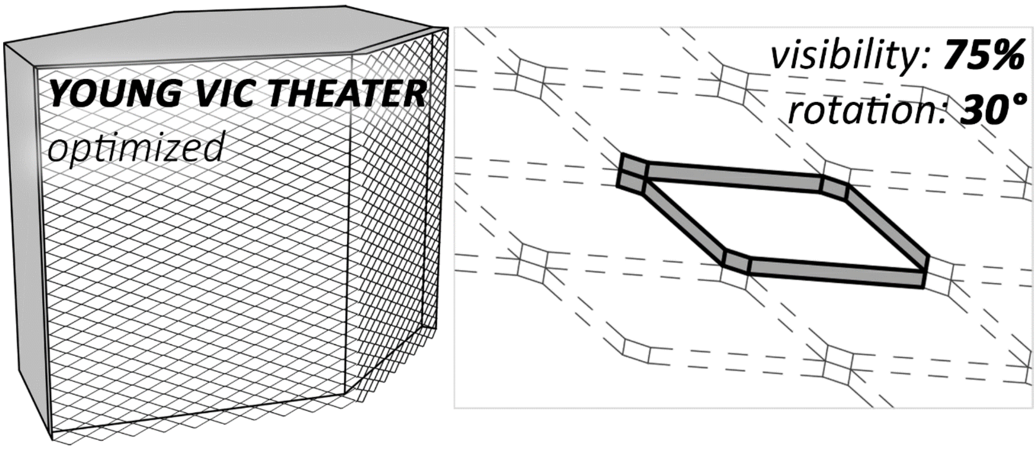


Figure 68: Diagram representing the geometrical parameter values for Young Vic Theatre, Credits belong to the author

After the result of the BBVA Stadium, the best results obtained is by **The Young Vic Theatre**, having 49.29 for the optimized customized spatial daylight autonomy value. As it can be perceived from the visual below, this case study model has two angled surface that taking the daylight from two different sides. While the main orientation can be considered as south; the glazing is also takin light from the south-west façade. That is why is can be considered slightly similar to the BBVA Stadium. Moreover, the fact that the size of the model, and the depth of it is much smaller than the other models that are analysis, including the simplified shoebox model; decreases the under-lit areas in a very significant way.

Thus, the lower value of the CsDA with the configuration without any shading is due to the over-lit areas which are closer to the glazing. That is why, the application on an efficient shading system, that is the geometrically optimized expanded metal mesh system; has an important impact for increasing the comfort. The proportion of the visibility percentage and the rotation of the strips is also showing the outcomes of having two different façades. 30 percent of the angle is rather higher than the ones facing only south, however with this value it is possible to compensate both faces. Another interesting comment would be about the visibility percentage that is higher. The building is located in London, England which has a cold and bloomy climate. Due to the insufficient levels of daylight for the majority of the time of the year, this value is higher.

10.1.4. MAISON FOLIE DE WASEMMEZ

	NO SHADING CsDA	**OPTIMIZED CsDA**	VISIBILITY PERCENTAGE	ROTATION OF THE STRIPS	IMPROVEMENT
MAISON FOLIE DE WAZEMES	24.94	**34.02**	*70*	*30*	*9.08*

Table 9: Optimization results for Maison Folie de Wasemmez

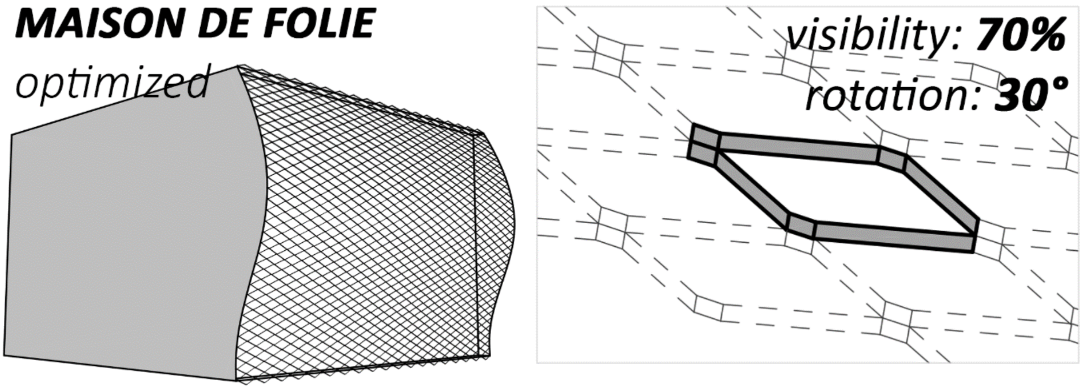


Figure 69: Diagram representing the geometrical parameter values for Maison Folie de Wasemmez, Credits belong to the author

The next interesting model to be analysed is the **Maison Folie De Wazemmes** located in Lille, France. This is the only model that has the single curvature surface façade which makes the daylight distribution of inside the space different than the others. The placements and the rotation of the whole surface plays a very important role for this design, because of the curvature. For the design that is take from the original building design, The curvature is placed in a way that after the half of the surface the surface starts to face down that is blocking the dun light incident from south not to be able to go inside, reducing the solar gains; which can be a strategic shading system for some of the climates. Even thought, the initial results were not as high, the expanded metal mesh worked well enough to increase the customized spatial daylight autonomy value to 34.02%. Moreover, even if half of the surface is faced towards down, the upper parts are angled towards up which make the sun light to enter in a more perpendicular way, which is why the areas closer to the glazing are highly over-lit and it is very difficult to control it by a shading device that has holes inside. 30 degrees of rotation angle and 70% of visibility, creates a great compensation for the overall surface, trying to control both the over-lit and under-lit areas. It is also interesting to observe the differences with the Premont Lantern example, where the floor area and the depth of the room are the same but the height of it is 1 meter higher for this case, which makes the analysis mesh to receive more direct light. As a consequence; the comfort levels in the areas closer to the glazing are lower for this case and this affects the overall value of the customized spatial daylight autonomy. However, it is also very interesting to see that the geometrical parameters are almost the same as The Young Vic Theatre, even if the climate conditions are much different. This shows the importance of the orientation and the shape of the floor that affecting the distribution of the daylight in a very significant way. (they both have the same illuminance thresholds: 500-2000 lux)

10.1.5. NEW YORK CONTEMPORARY ART MUSEUM

	NO SHADING CsDA	**OPTIMIZED CsDA**	VISIBILITY PERCENTAGE	ROTATION OF THE STRIPS	IMPROVEMENT
MUSEUM OF CONTEMPORARY ART	27.55	**29.08**	*90*	*10*	*1.53*

Table 10: Optimization result for the New York Contemporary Museum of Art

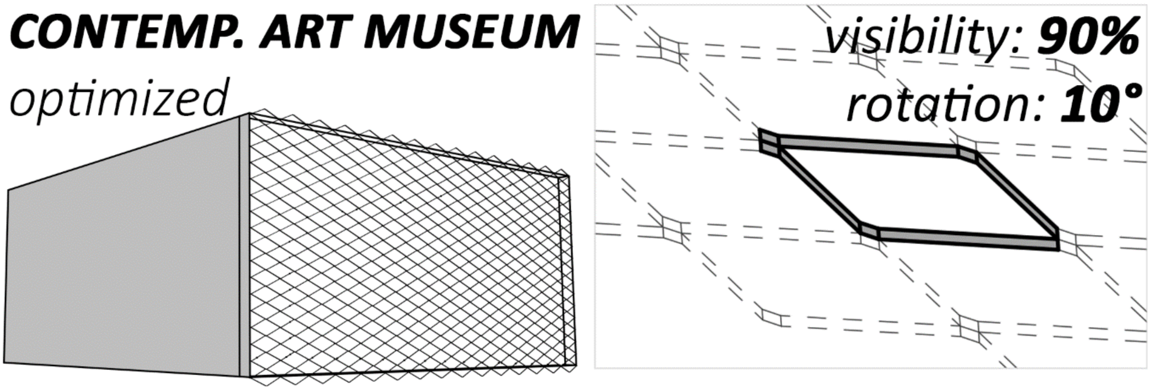


Figure 70: Diagram representing the geometrical parameter values for Contemporary Art Museum, Credits belong to the author

The New York Museum of Contemporary Art is the only case-study building for which the application of expanded metal mesh as a shading device did not increase the comfort in an efficient way. As it can be seen from the visuals of the comfort distribution graphs, both the under-lit areas located in the back of the room, and the over-lit areas closer to the glazing; are creating a problem for the indoor comfort. Unfortunately, the trial of optimizing different geometrical parameters for the mesh did not work to solve this problem, even though the optimization process is applied in the same method and time range. The results given by the software are 90% of visibility and 10 degree of rotation of the strips; is indicating that it is not necessary to use expanded metal mesh for this case study building. However, in the description part of this museum, it was explained that the reason why this material is used for the façade of the building is due to aesthetical and conceptual reasons. Moreover, the usage of artificial light is highlighted even in the photos that are taken during the daytime. Another parameter that is affecting this is the depth of the building that is a lot and the nearby building which are making it impossible to get daylight from the other façades.

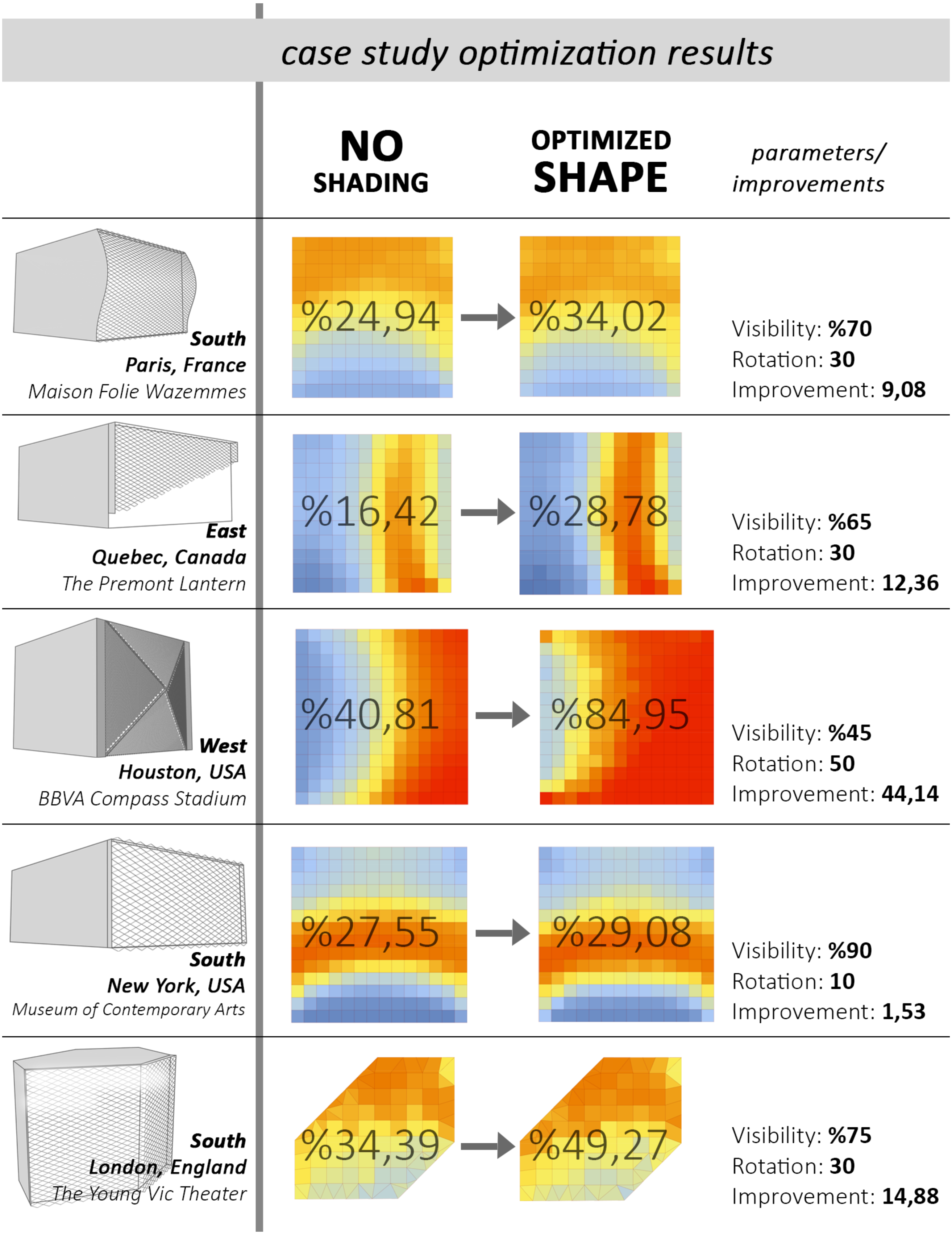


Figure 71: Diagram showing the comparison of the CsDA distributions on the analysis meshes, for the case study optimization configurations

METHODOLOGY

11. *Optimization of the EMM, adapting to various surface typologies*

The final, and the most important part of this thesis research is the "Optimization of Expanded Metal Mesh, Adapting to Different Surface Typologies" which will be investigated in this chapter, thanks to all the previous simulation and analysis steps that has been made. The main purpose of this final analysis step is to give the architects and designers different option for the surface typologies to be applied on, as well as proving that both the shading system and the optimization methodology is working very well and that the expanded metal mesh can be used in many different climates, especially for south façade. This final grasshopper script would be the final project result of this research paper. As the user changes and introduces the epw weather file and the surface; it would give the optimized values for the visibility percentage and the rotation of the strips; ready to be given to the produces, making sure that the expanded metal mesh applied as a shading exterior cladding, will improve the indoor daylight comfort in the best way possible.

Until arriving to this phase, many important decisions have been made as a result of the state-of-the-art research as well the preliminary optimizations and simulations. Here is a summary of the important steps and the decisions that are made with regards to them.

First, the preliminary shoebox analysis has been made to understand the behaviour of the parameters within changing contexts (locations) and four different orientations. How the geometrical parameters were changing depending on the inputs; moreover, how the indoor comfort levels are related with the performance of the expanded metal mesh is observed. An important decision has been made regarding the outputs of these simulations. It is the fact that south façade is the orientation which has the most important and significant impact on the application of expanded metal mesh. **Which is why for the next simulations, going in depth with the analysis of south orientation has been decided.**

Secondly, the optimization process with octopus have been initiated. Two geometrical parameters with clear limitations are defined as the genomes and the customized spatial daylight autonomy as the fitness. Then the same model for south façade is optimized for the two different climates; Oslo and Milano. **This first optimization showed us how much time is needed to be dedicated for the process and how much improvement can be obtained for these climates; so that it will be know if the optimization is efficient and necessary or not.**

The last step before the surface adaptation, was the optimization of the case-study buildings, using the same inputs and the same optimization procedure. Thanks to these simulations that are made for different model geometries, glazing and shading surface, functions and illuminance ranges and even the orientations; it was proven that the expanded metal mesh is working very well for most of the (4 out of 5) cases. **This was the reality check point that allowed the material to be investigated further.**

After collecting all these outputs and understanding every aspect of what has been done, the surface adaptation phase is confirmed to be started.

This first step to be taken was to decide on the types of surfaces to be modelled from and how the expanded metal mesh could be adapted to it. The adaptation should have been in such a way that the visibility percentage and the rotation of the strips parameters are working and behaving in a clear and expected way, which was the most difficult part of the process. There have been many scripting trials to represent all the important aspects, within the tools of grasshopper. **In this chapter, one of the most enlightening trials will be explained and then the final methodology will be presented with the optimization results and outcomes.**

11.1. Critical Surface Adaptation

This chapter is dedicated to explaining the process where the critical surfaces are selected and how the adaptation of the expanded metal mesh has been done. First of all, it was necessary to define the fixed inputs for the model since the only variation that was needed to implement was the change of the shading surface. In order to decide on the model size, function, and the illuminance range to be used in all the analysis; case study simulations are taken as a reference.

The New York Contemporary Museum of Art has been the only case study building on which the expanded metal mesh was applied and did not give efficient results in terms of the increasing the indoor daylight comfort. This was because of the fact that it was located in a cold climate and the placement/location of the building was not letting the façade to work in a sufficient way to receive daylight in a controlled way. That is why it was decided that, in terms of the size of the model the same measurements would be used which is 7 m*7 m*3,5 m . It was a strategic model, also in terms of the fact that it was within the limitations of the shoebox modelling requirements. (in terms of the height and depth proportions). However, the shoebox model that was built before had the "Gallery/Museum" function which had different ranges for the comfort illuminance levels inside. That is why, it was decided that the function would be changed as OFFICE which has the comfort levels between 300-2000 lux which would be a more generic value to be used for further studies. The orientation was kept the same as south façade and as a result of the dimensioning of the model the floor is became approximately 50 m^2. (with the addition of the space in between the shading surface and the glazing. Here is a summary of the inputs that are used for the last template model on which the different surfaces would be applied.

INPUTS
Orientation: South
Function: Office
Threshold: 300-2000 lux
Floor Area: 50 m2 (approx.)
Height: 3.5 m
Room Depth: 7 m

Table 12: Description of the inputs

Activity	Illumination (*lux, lumen/m²*)
Public areas with dark surroundings	20 - 50
Simple orientation for short visits	50 - 100
Working areas where visual tasks are only occasionally performed	100 - 150
Warehouses, Homes, Theaters, Archives	150
Easy Office Work, Classes	250
Normal Office Work, PC Work, Study Library, Groceries, Show Rooms, Laboratories	500
Supermarkets, Mechanical Workshops, Office Landscapes	750
Normal Drawing Work, Detailed Mechanical Workshops, Operation Theatres	1,000
Detailed Drawing Work, Very Detailed Mechanical Works	1500 - 2000
Performance of visual tasks of low contrast and very small size for prolonged periods of time	2000 - 5000
Performance of very prolonged and exacting visual tasks	5000 - 10000
Performance of very special visual tasks of extremely low contrast and small size	10000 - 20000

Table 11: Illuminance ranges depending on the activity, Credits: noao.edu/education/QLTkit/ACTIVITY_Documents/Safety/LightLevels_outdoor+indoor

After determining the fixed inputs, the critical surfaces to be analysed needed to be defined. Since there was also the time limitation of the simulations; it was decided that only the most strategic and interesting ones would be analysed in depth. Single degree curvature surface that was inspired by the façade of the Bocconi University was the first option and the curvature is given in the horizontal direction so that the problem of facing down would not happen. The second one was the double degree curvature surface which was exploring the possibility to adapt on complex surfaces. The dome window surface is selected as the last option due to the different and challenging qualities of the dome structures. (the window is copied 2 times to cover almost the whole south façade with the shading surface so that the size of the glazing area would be a common ground for all the configurations and it would make it possible to have a comparison between them)

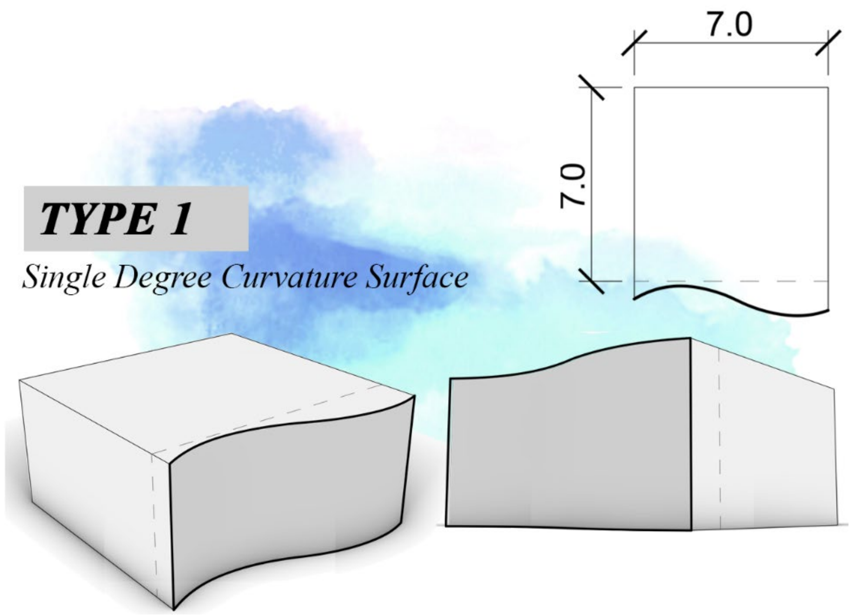


Figure 72: Diagram describing the TYPE 1 surface, credits belong to the author

The first type of surface is modelled by drawing the curve that is consisting of two arches that is a part of a circle copied and mirrored and connected. The extruded in a flat way through the x axis. This variation takes its inspiration from the Bocconi University façade where the expanded metal mesh is used in a successful way.

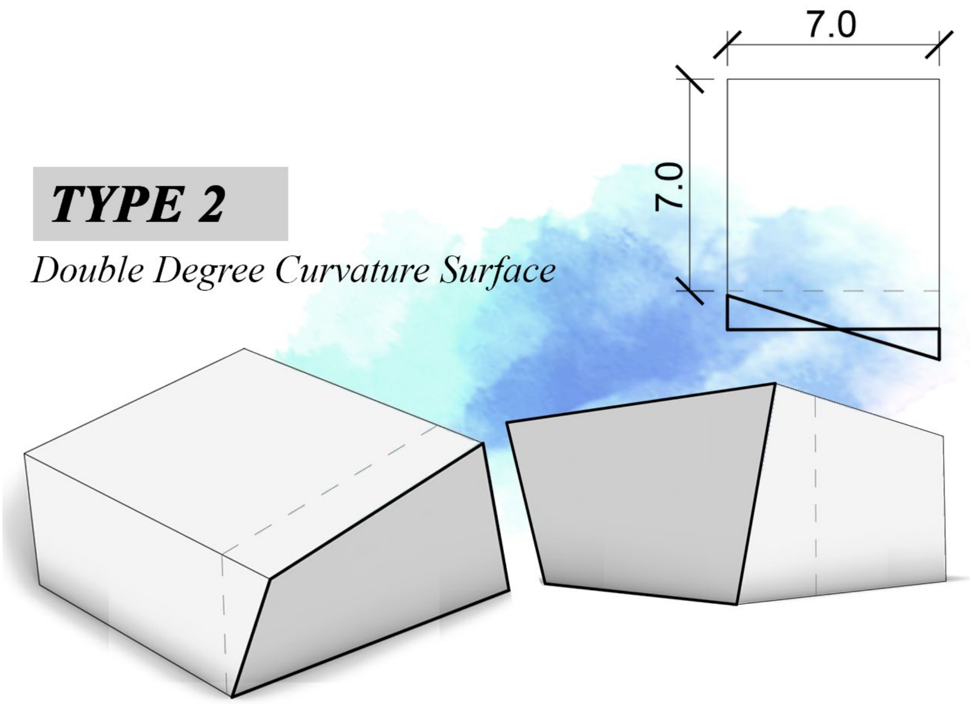


Figure 73: Diagram describing the TYPE 2 surface, credits belong to the author

The second type of the surface is a double curvature complex surface that is made out of a flat surface that is deformed from its corner points, by moving them on the perpendicular direction. It was interesting to try the adaptation to a double curved surface since it has many different variation possibilities due to the deformation. (to be able to stretch towards other orientation to receive to block the daylight further)

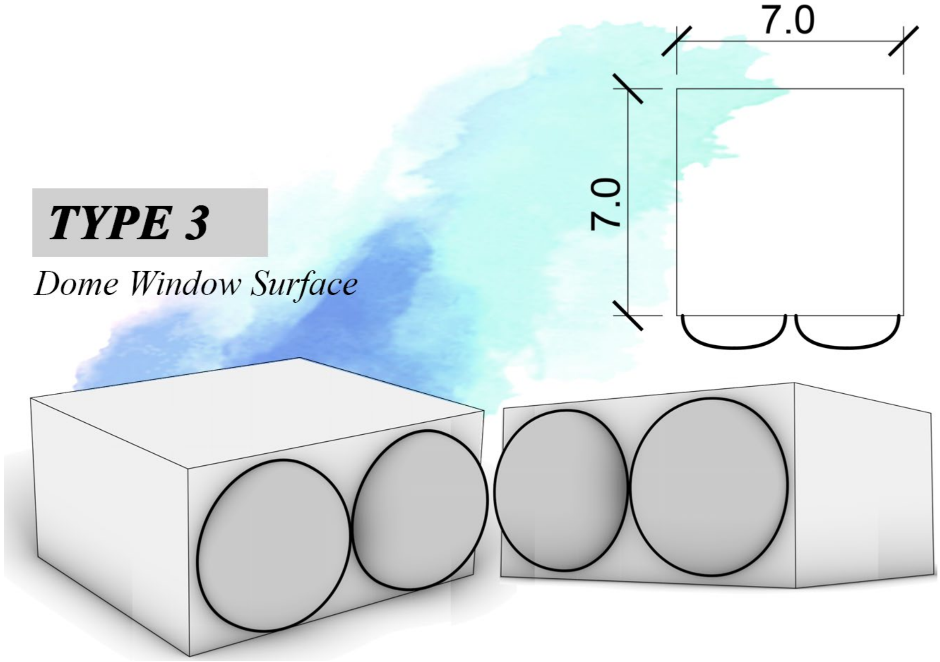


Figure 74: Diagram describing the TYPE 3 surface, credits belong to the author

The type 3 surface is the most challenging type to be able to adapt due to the properties of a dome structure. The surface is created by drawing an arch in the xz plane and then using the revolve component to draw the surface from the arch repeated in 360 degrees.

In the previous pages; the visuals of the different surface types are represented in a simplified way. After defining and modelling these surfaces on Rhino and introducing them on grasshopper; it was time to adapt the expanded metal mesh on them.

The adaptation is made with different scripts but with the same mentalities. The first step is the same as the other simulations, a module for the expanded metal mesh is created where the main geometrical parameters are implemented. For the flat façade; this module was arrayed along both sides of the rectangular glazing surface so that the whole façade is covered with the expanded metal mesh. While for the curved surfaces this methodology does not work since the curves for both sides have different properties, and the surface is created by more than 2 curves. The new methodology for applying the small module works much better for this adaptation.

The surface is divided into a grid made out of points. The number of the points in each axis is calculated with regard to the modules size (the is changing parametrically). The length of long side of the surface is divided to the length of the long side of the module. The same is repeated for the short sides. This way, the pattern would be fitted perfectly. Then the module is copied from its centre to these points. However, simply moving and copying them is not enough because the normal vectors of the pattern needs to be changes accordingly with the normal of the points on the surface. That is why the component “orient” is used instead of “move”. This is how the parametric adaptation of the type” surface and type 2 surface are done.

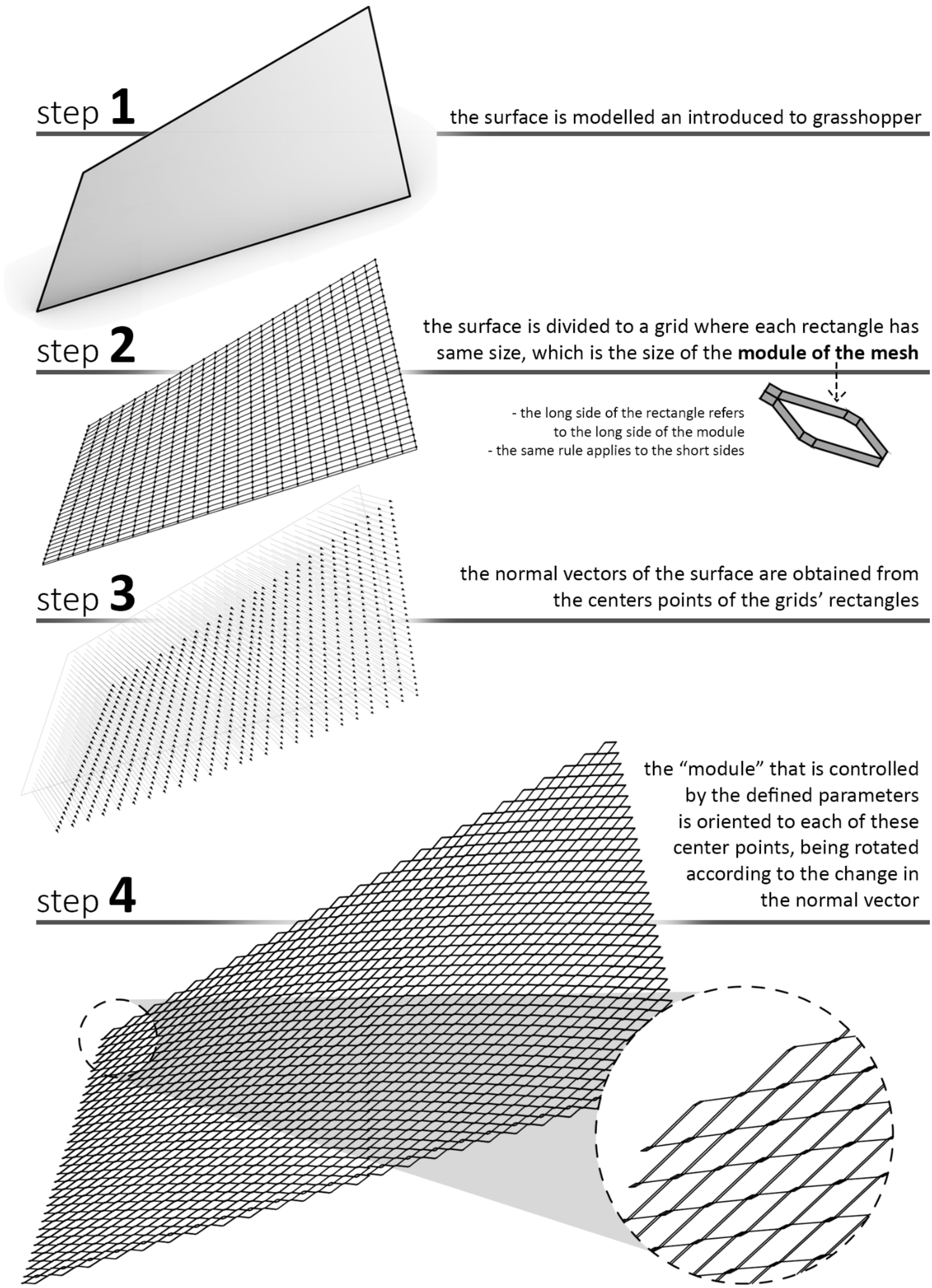


Figure 75: the explanation of the process of adapting the expanded metal mesh to a complex surface

Here is an adaptation visual of the **TYPE 1** surface. The methodology worked very well for this surface since it is the simplest one among all. The slight curvature that is inspired from the Bocconi University's façade where expanded metal mesh is used in a very interesting way, is letting the shading device to work for different angles.

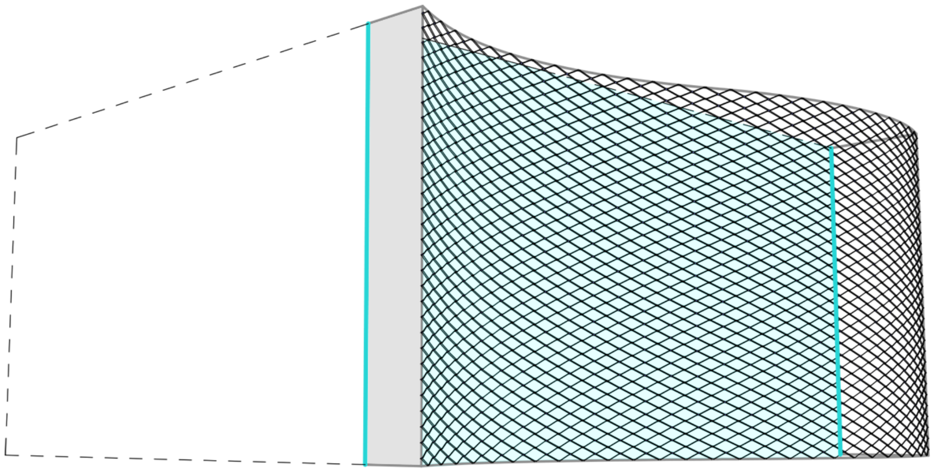


Figure 76: Drawing about EMM applied on TYPE 1 surface typology, credits belong to the author

For the **TYPE 2** façade the same methodology has been applied. The point grid is created taken the input as the surface itself, not the curves that are described by it. So that the length measurement would fit perfectly without having holes between the modules. However, when the module size, meaning the hole size reaches its maximum values, the simplification creates a small problem where there are very small holes (around 0.2 cm) between the patterns. However, the main purpose of this research is not to create a script which is modelling the expanded metal mesh with a realistic penalisation that is ready to be produces; but to investigate the daylight performance of it. That is why, this error was accepted for the simulations.

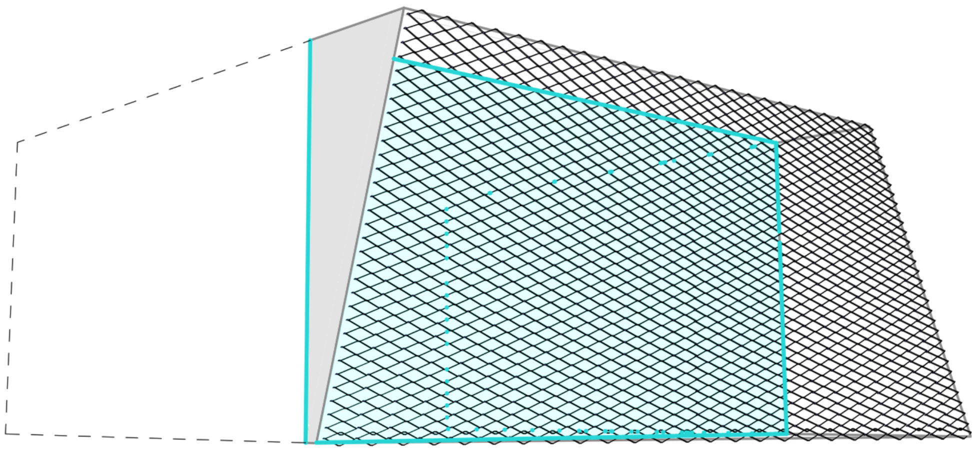


Figure 77: Drawing about EMM applied on TYPE 2 surface typology, credits belong to the author

TYPE 3 surface that is created by a dome structure which is made my revolving an arch 360 degrees. The dome structure can be considered as being consisting of many intersecting curves. That is why, it is impossible to use the same system where a point grid is implemented. Since the distance between the points of the grid would decrease as approaching to the tip point of the dome, the pattern would have been stretched not having the same dimension everywhere. The parameter control is the key factor of this surface adaptation, which is the reason why another strategy where all the pattern/modules sized are the same is developed.

The flat part of the dome (where the glazing is) is defined as the reference plane of the script. First a surface is created parallel to that plane. Then that surface is copied in the direction of the plane through the middle tip of the dome. The copying of this surface is made by a linear array where the distance between the surfaces is calculated by dividing the length of the centre line to the length of the short way diamond distance of the module. Then the intersection curves (circles) between the dome surface and the flat surfaces that are repeated are obtained. Afterwards, the module is moved on the top point of the dome, also transforming the normal vectors as well. Then a "polar array" along the biggest circle with that module is made. This time, the number of the elements are calculated by dividing the length of the big circle to the long way distance of the module, so that it is fitted in a perfect way. The same procedure, starting from moving the module to the tip of each circle is repeated so that in each circle there are different numbers of modules. (in order to keep the dimension and parameters the same and controllable)

Thus, this way of modelling is creating some errors as well since the circles cannot be repeated in the tip of the dome. That is why a small hole emerges. However, this simplification is acceptable for the simulations where the comparisons and the performance of the materials has the most importance.

Below there is visual of the final model with example values for the geometrical parameters.

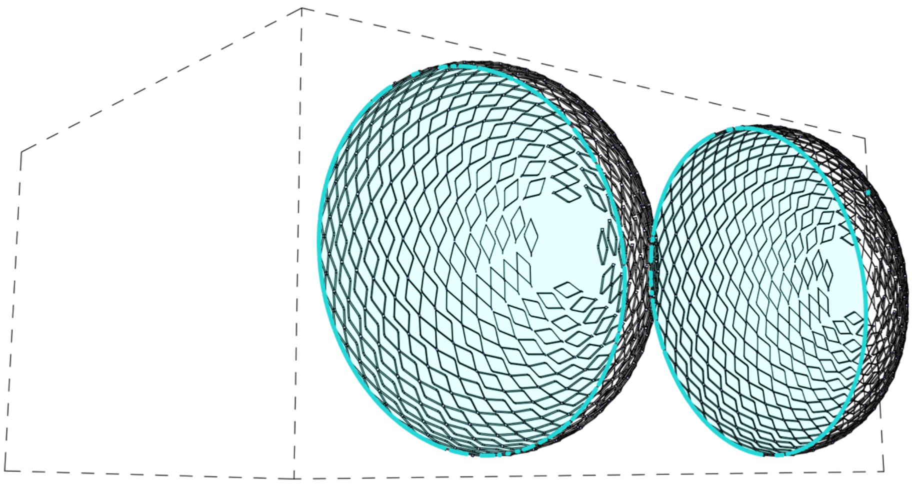


Figure 78: Drawing about EMM applied on TYPE 3 surface typology, credits belong to the author

These 3 surfaces are defined as the most critical adaptation surfaces and after all these steps are achieved having room for errors for the simplification; the models are introduced to the Honeybee zones, ready to be simulated for the optimization process.

12. *Optimization Results of the Critical Models*

The Octopus optimization is the key point of this whole process. After the Honeybee zones for each configuration is defined; the simulations have been made for each of them before initiating octopus. In order to be able to compare the results also with the simple shoebox model simulations, it is decided to make the optimizations, again, for two different climates that are Oslo and Milano, with the model inputs that are explained before. The parameters that would be optimized are the visibility percentage (in the ranges between 40% and 90%) and the rotation of the strips (ranges between 5 degrees and 85 degrees) and the optimization would be made with regards to maximizing the Customized Spatial Daylight Autonomy. The analysis mesh is the floor size of the shoebox and it is elevated from the ground 0.75 meters and divided into a grid that is 0.5 meters in each direction. Then the geometrical parameters that is desired to be investigated are connected to the genomes of the octopus component. (visibility percentage and the rotations of the strips). Then the customized spatial daylight autonomy result number is connected to the fitness of the same components. The optimization analysis is running for 24 hours for each configuration, since it was perceived that more complex surfaces require more time than the flat and simple ones.

FINAL OPTIMIZATION							
INPUTS	LOCATION	SURFACE TYPES	**NO SHADING CsDA**	**OPTIMIZED CsDA***	VISIBILITY PERCENTAGE	ROTATION OF THE STRIPS	DELTA
Orientation: South	MILANO	TYPE 1	43.26	**69.01**	40	20	25.75
Function: Office		TYPE 2	47.61	**70.23**	65	50	22.62
Threshold: 300-2000 lux		TYPE 3	41.66	51.19	90	10	9.53
Floor Area: 50 m2 (approx.)	OSLO	TYPE 1	28.30	48.8	40	10	20.5
Height: 3.5 m		TYPE 2	30.95	**51.78**	60	10	20.83
Room Depth: 7 m		TYPE 3	26.50	41.66	90	30	15.16

Table 13:CsDA results comparison of the surface typology configuration represented with the optimized results and geometrical parameters

When the octopus optimization is stopped, the point on the curve that indicates the maximum value of CsDA is selected and the simulation is made again to see the what the parameters that make it possible are. Then, the results are transferred on an excel sheet in order to collect everything together for the comparison of the results. Moreover, the mesh distribution of the results is saved to see the differences in different areas, keeping in mind the improvements obtained compared to the no shading option.

The chart above is representing the summary of results where, the input parameters, different analysis locations, surface types, CsDA values without any shading device, CsDA values with the optimized expanded metal mesh as the shading device, the geometrical parameters values and the improvements that are calculated by subtracting the optimized value from the no shading value are present. Even from the summary of the results, it is obvious that the optimization of the expanded metal mesh is working very well for almost all the configurations. The CsDA results for Milano and Oslo were 47.61% and 30.95% in order, which are not good enough for a sufficient levels of daylight comfort inside, considering that suggestions from the designers about the CsDA value is that, it is required to be above 50%. For Milano, it is observed that all the configuration are achieving to be increase above 50% by the help of the optimization methodology, while for Oslo that has a colder climate, except for type 3; the other two configurations have been managed to be around 50% threshold. Since the same shoebox model of the New York Contemporary Art Museum where the expanded metal mesh did not have any significant impact on the daylight comfort is used, it is also proving the importance of the location of the application to be able to exploit the performance of the mesh.

The other reason that Type 3 did not give sufficient results is the method of controlling the dome surface. The dome is placed in a vertical way on the glazed windows, giving the structure to receive daylight from 4 different faces: top, 2 sides and bottom. This characteristic of this surface type requires the dome to be divided into at least 4 different parts, in order to provide necessary shading and daylight control regarding the differences in each side. However, for the purpose of the optimization analysis, this methodology was not possible to be applied within the time frame that is defined. To be able to manage this accurate control, the optimization parameters had to be increased from 2 (visibility percentage and rotation of the strips) to 8 (2 different values for each mentioned side); which leads to the simulation time to be increased significantly. That is why, for the sake of simplification, the whole dome surface has been decided to be controlled in the same way as others; with 2 different parameters for every side of it.

Even though the summarized results are showing the efficiency of the methodology, it is crucial to look into the results in more depth by checking the distribution of the comfort inside the whole subjected space, as well as perceiving the geometrical translations of them. Below, both the mesh distributions and the geometrical properties of the results are represented.

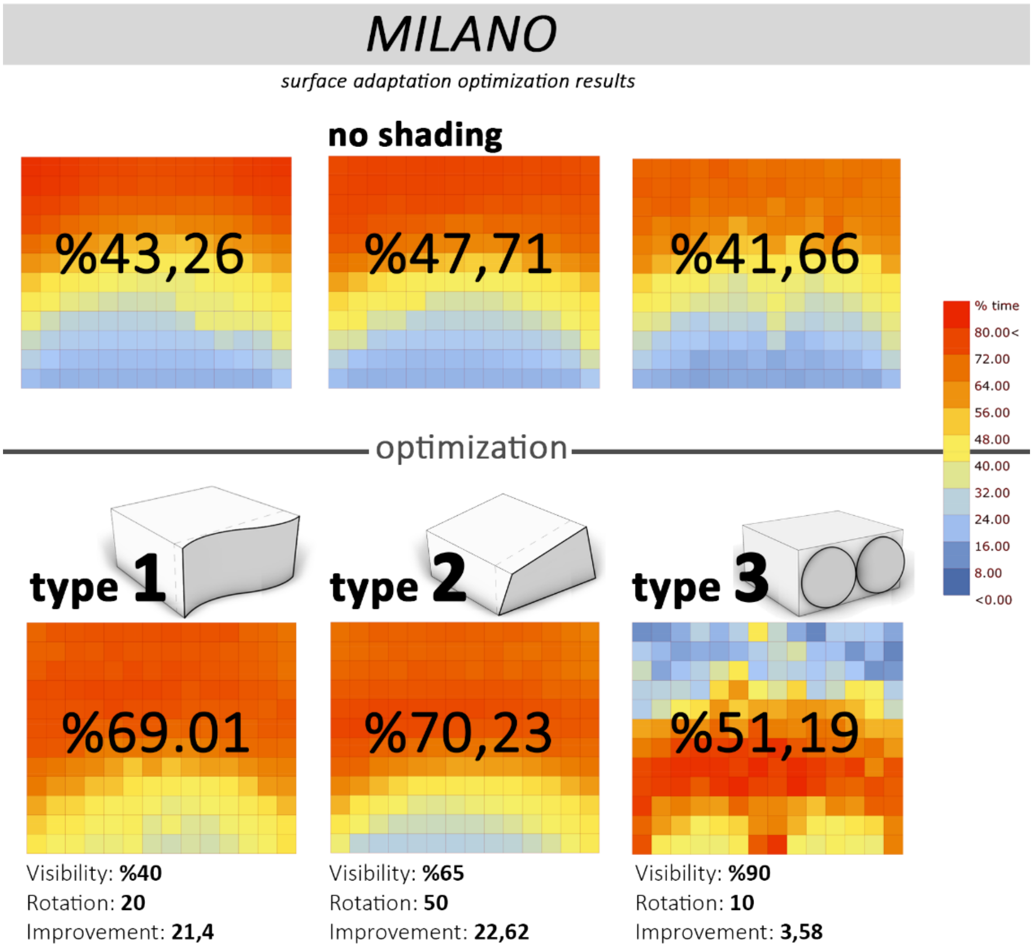


Figure 79: CsDA distribution results comparison between the optimized and initial cases for Milano

Staring with Milano, which had better results rather that Oslo because of if its hotter climate that requires a shading strategy for longer period; it is clear that the main reason for the discomfort inside the room was due to the areas closer to the glazing. While the deeper areas had good results, not having under-lit areas. The improvements are indicating solely the impact of the shading device that is decreasing the over-lit areas. The best improvement is achieved by the Type 2 configuration, increased up to 70,23%

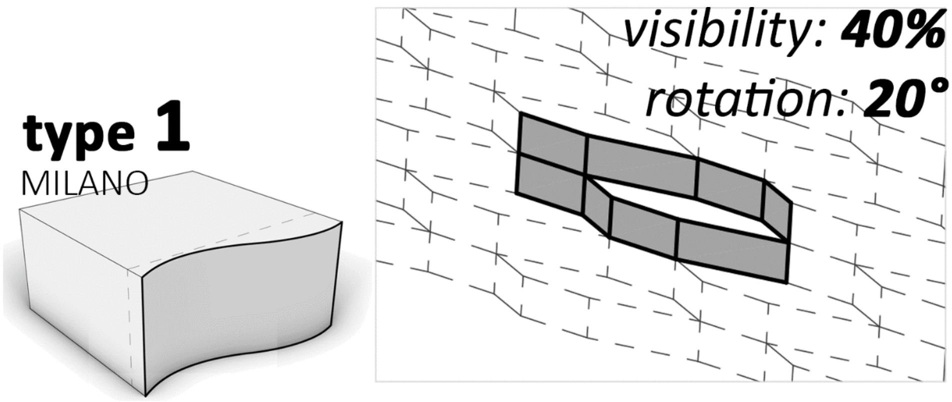


Figure 80: Optimized parameter representation of TYPE 1 for Milano, Credits belong to the author

The optimized version of the Type 1 configuration is achieved by 40% of visibility and the 70 degree of the strip angle and the best CsDA value for it is 69.01%, which is 20% more than the initial state. Since the façade it directly facing the south façade, also gaining some solar gains from east façade the visibility percentage became the lowest value possible. Moreover, the angle of the strips is showing similar results as the flat façade configurations that are made for the south façade.

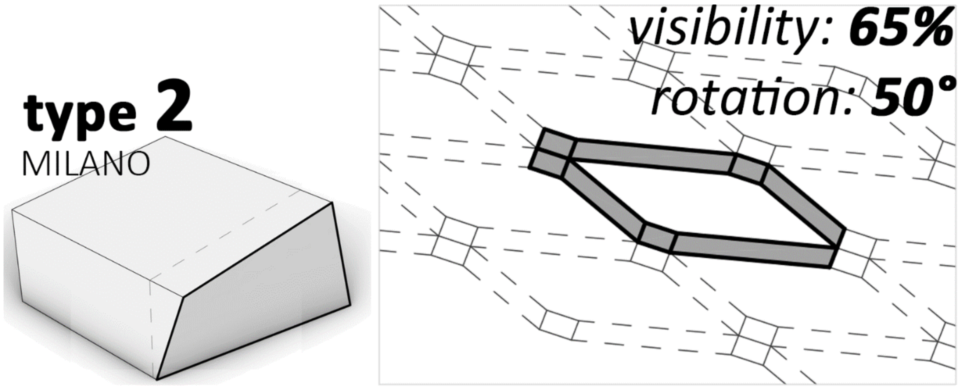


Figure 81: Optimized parameter representation of TYPE 2 for Milano, Credits belong to the author

The type 2 configuration for Milano, has the best improvement by increasing the CsDA value to 70.23% while having the visibility percentage as %65 and the angle of the strips as 50 degrees. The main reason for obtaining the best results with this configuration is due to the deformation of the surface from the top corner of the façade. This point is pulled along the same line to the opposite direction and made the top part of the shoebox act as a small overhang which is also adding to the shading performance of the system. Moreover, having daylight from different directions thanks to the stretch of the surface makes the daylight more controllable. Because of this advantage of the additional shading effect, the best CsDA value is obtained without having the lowest value of the visibility; 65%. Thus, the rotations of the strips have the medium value, which is proved to be the best option for south oriented configurations.

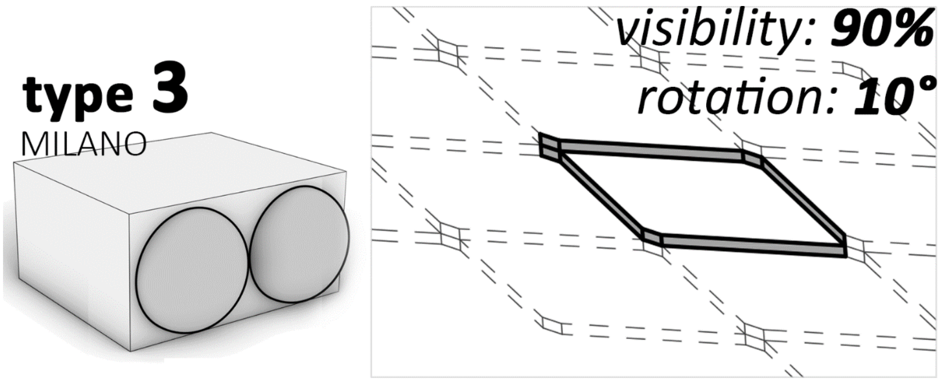


Figure 82: Optimized parameter representation of TYPE 3 for Milano, Credits belong to the author

The type 3 configuration was the worst one for both of the locations. Only for this configuration, the glazing surfaces are not covering the whole south façade. That is why it is causing the deeper areas of the analysis mesh to be under-lit by not receiving enough daylight. Thus, the daylight comfort level is decreasing significantly compared to the other cases. Moreover, due to the presence of a dome structure for the shading device oriented in the south façade; only half of the shading system is affecting the daylight control which also makes the over-lit areas not be decreased. Since the shading device is not efficient the geometrical parameters are taking the least common values where the visibility percentage is 90% and the rotation of the strip is 10 degrees.

According to these results; it can be stated that the dome window structure does not work very well for Milano south orientation and it is not suggested to be implementing the expanded metal mesh in this way. However, for the other types of surfaces that are optimized, the results are very satisfactory and offering a wide range of different application strategies, since there are endless options for the single degree and double degree surfaces.

Another important comment would be that, by the help of these curvatures that are obtained; it would be possible to have an effective daylight control for the other façades, while adapting the geometrical parameters and arranging the surface properties in such a way that the direct daylight coming from east and west orientations are avoided. This strategy not only optimizes the performance of the expanded metal mesh but also gives opportunities to be used within different designs.

The next location that is observed is Oslo, that is giving similar but less efficient results in general than Milano. As discussed before this is due to the fact that Oslo has a colder climate which makes the discomfort given by the under-lit areas more significant.

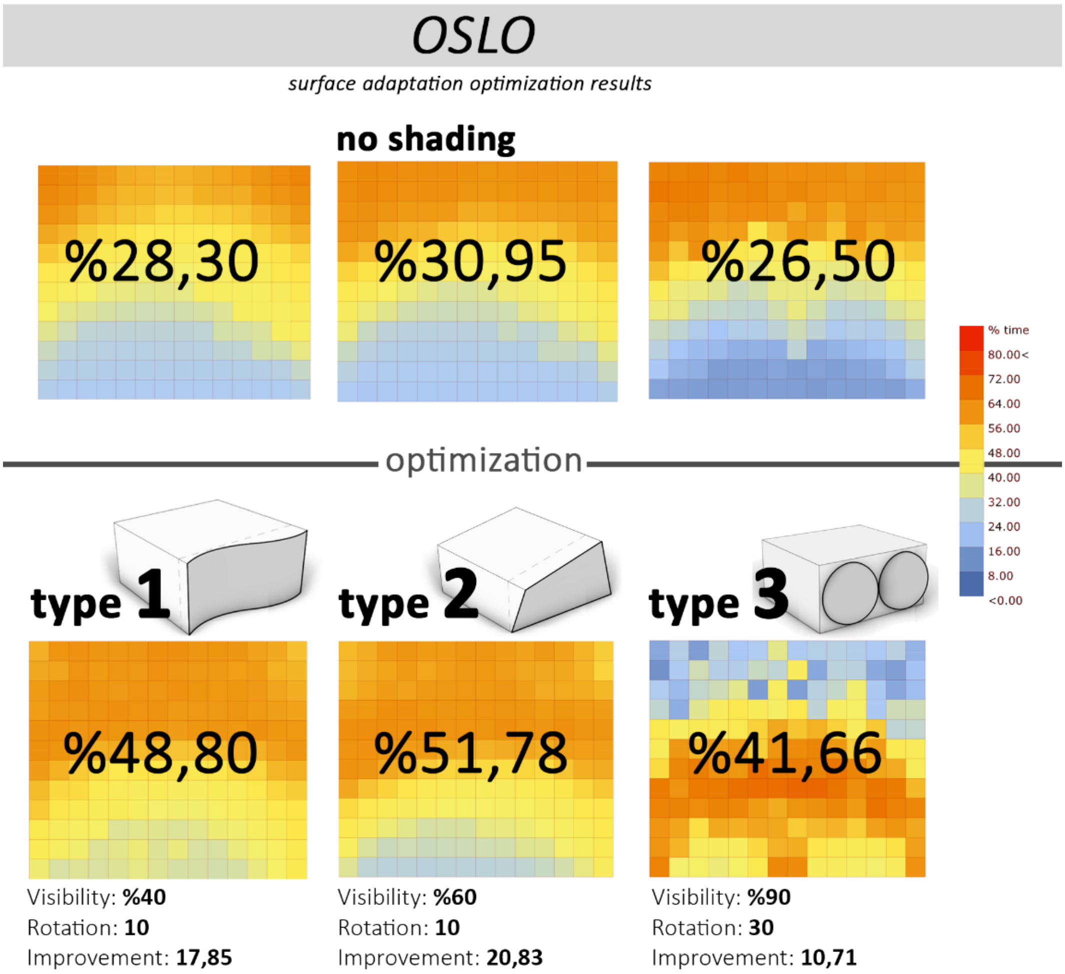


Figure 83: CsDA distribution results comparison between the optimized and initial cases for Oslo

The Type 1 surface optimization results in an efficient increase up to 48.80% of CsDA. The improvements that are achieved are directly related to the control of the areas near the glazing. The comfort is increased thank to the shading effect of the expanded metal mesh for all the cases. The under-lit areas located in the deeper part of the room are not affected much by the presence of the shading device, while the customized spatial daylight autonomy in the middle parts have increase significantly for the first two cases.

The performance of expanded metal mesh is quite similar in both of the climates since the even though the starting points are different the improvements in comfort are close to each other. Especially for the first two cases the proportions go hand in hand. An important difference of the results would be the fact that, for the third case, a much better application result is observed. This is probably cause by the direct light coming inside form the middle opening and hitting the middle part of the analysis mesh.

Moreover, there is an interesting similarity in the way geometrical parameters a behaving for each configuration. Going from type 1 to type 3, the visibility percentage increase proportionally for both climates. While type 1 has the lowest value for the visibility, type 2 has the middle value with the help of the additional overhang comes within its design, and the type 3 gets 90% of visibility showing that the configuration cannot exploit the advantages of the shading impact of expanded metal mesh.

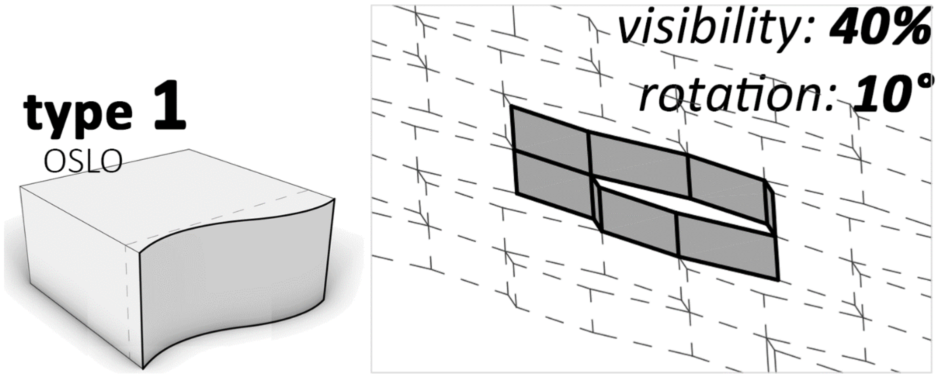


Figure 84: Optimized parameter representation of TYPE 1 for Oslo, Credits belong to the author

Type 1 that is a curved surface that is extruded in a straight way in the z axis, receives the most amount of direct daylight that, the visibility percentage gets the lowest value possible for both the climates; 40%. While for the rotation, it is 10 degrees which is very close to the flat variations that is the best one in terms of blocking light coming from the south façade.

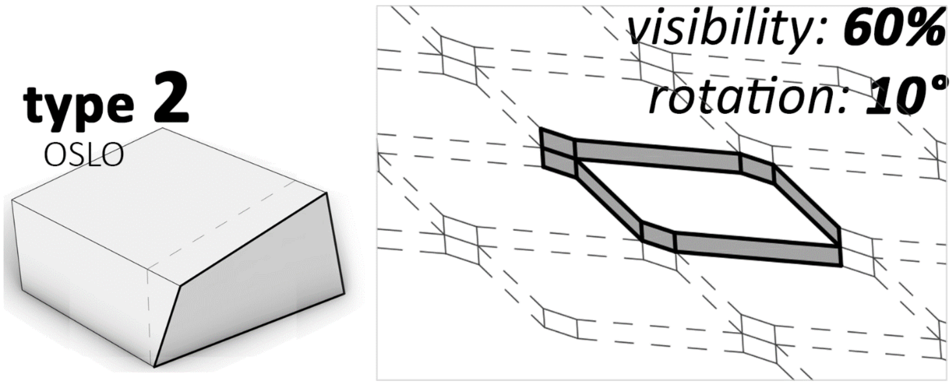


Figure 85: Optimized parameter representation of TYPE 2 for Oslo, Credits belong to the author

The visibility percentage that is 60% is again very similar to the previous case with the hotter climate, however the angle of the strips has a significant difference that is 40 degrees. For this configuration, the strip gets the angle of 10 degrees, getting closer to a flat variation to be able to control daylight further. This means that the deformation of the glazing surface did not affected the indoor comfort in a positive way. However, looking at the results shows us that Type 2 application is the best way among the modelled spaces that exploits the performance of expanded metal mesh by increasing the customized spatial daylight autonomy significantly.

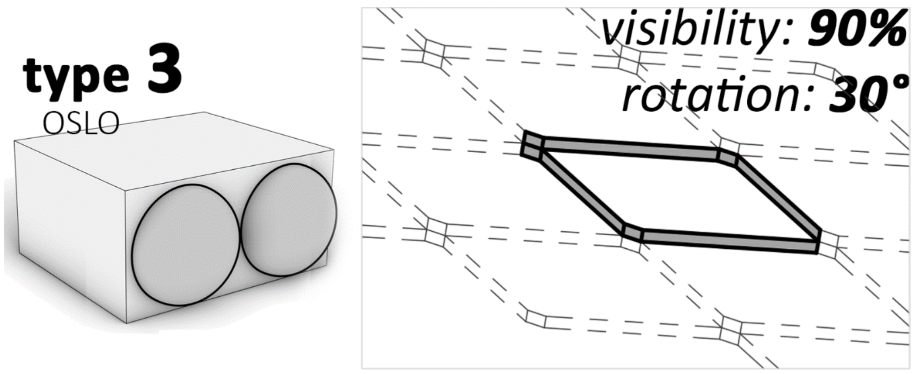


Figure 86: Optimized parameter representation of TYPE 3 for Oslo, Credits belong to the author

As a result of the optimization process that has been done for; a simple flat shoebox model, five case-study buildings and 3 different surface typologies, it was proven that in terms of indoor comfort that is measured by customized spatial daylight autonomy, the expanded metal mesh has an efficient shading impact for most of the cases, by exploiting the geometrical parameters.

The comparison analyses are made only in terms of the CsDA that is indicating the areas that are withing the comfort levels, defined by illuminance thresholds. It is important to remember that this result is a average value for all year. Since the designed expanded metal mesh is considered to be static, it is a good assumption to be used while making decisions about the parameters.

To explain the results of the process of this research, it was decided to go into more detail with 3 selected configurations and realize the different measurement methodologies as; daylight factor, annual radiation, illuminance levels, daylight glare probability and annual glare hours average, to understand the benefits of the methodology from different aspects.

13. Bestest Configurations of the Optimization Process

The customized spatial daylight autonomy values obtained from the final octopus optimization process were indicating that except for type3/Milano configuration; all the configurations were increasing the indoor comfort in a significant way, in such a way that the over-lit areas managed to be decreased in a significant way. It is confirmed that for both of the subjected climates, expanded metal mesh is useful to be applied as an exterior cladding.

In order to answer the question of "**Is it really worth is to be applied as a shading device?**", it is essential to analyse the cases where the comfort increase is significantly observed. Since the difference between the CsDA value of the optimized case and the case without any shading device reaches the highest for the three configurations listed below, it is decided to select them as the bestest configurations. They are all exploiting the geometrical parameters in such a way that over-lit areas are managed to be decreased, in proportion to the climate conditions. The visibility percentage captures the attention having similar value for type 2 for both of the climates, while the rotation of the strips is varying more significantly, with respect to the sun angle of the south façade.

The parameters affecting the daylight comfort of a building according to this research can be summarized as;

- The geometry of the expanded metal mesh (Hole size/ Visibility percentage and Angle of the strips)
- The climate where the building is located
- The orientation of the façade
- The type of surface on which it is applied
- The function and the size of the space

Below, the summary of the selected bestest configurations are represented in terms of customized spatial daylight autonomy.

LOCATION	SURFACE TYPES	NO SHADING CsDA	OPTIMIZED CsDA	VISIBILITY PERCENTAGE	ROTATION OF THE STRIPS	DELTA
MILANO	TYPE 1	43.26	**69.01**	40	20	25.75

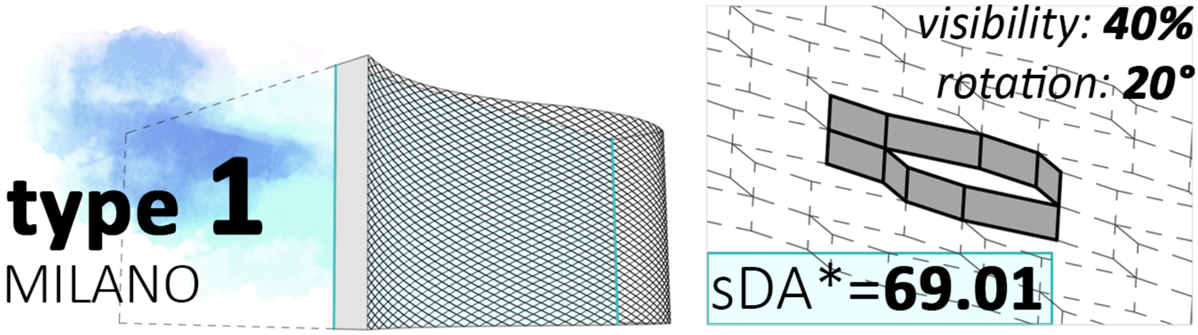


Figure 87: The description of the selected cases: TYPE 1 Milano

LOCATION	SURFACE TYPES	NO SHADING CsDA	OPTIMIZED CsDA	VISIBILITY PERCENTAGE	ROTATION OF THE STRIPS	DELTA
MILANO	TYPE 2	47.61	**70.23**	65	50	22.62

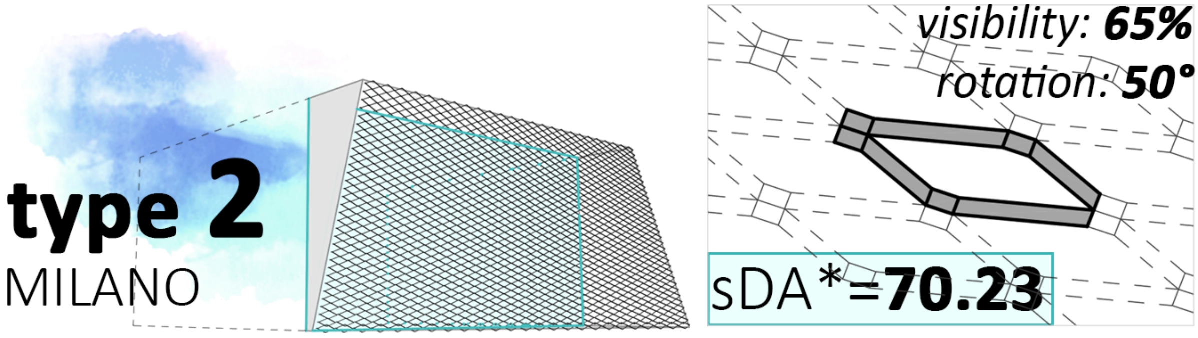


Figure 88: The description of the selected cases: TYPE 2 Milano

LOCATION	SURFACE TYPES	NO SHADING CsDA	OPTIMIZED CsDA	VISIBILITY PERCENTAGE	ROTATION OF THE STRIPS	DELTA
OSLO	TYPE 2	30.95	**51.78**	60	10	20.83

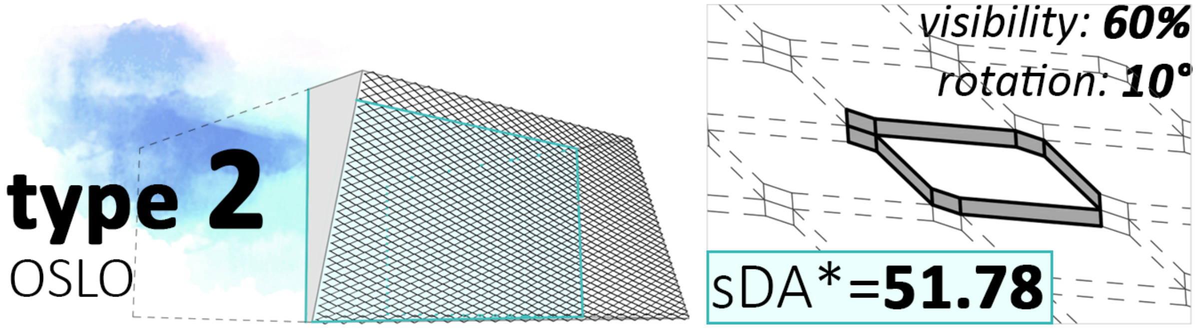


Figure 89: The description of the selected cases: TYPE 2 Oslo

14. Detailed Analysis for the Bestest Configurations

The methodology of understanding optimization process of expanded metal mesh was to compare the different configurations in a common ground that is selected as the customized spatial daylight autonomy. The importance is given to the indoor comfort to find the optimal values of the geometrical parameters. Even though, it is giving relevant information about the daylight comfort inside, there are many other aspects that are affecting it. Not only its sufficient daylight performance, but also the ability to reduce the solar energy gains leading the building to have energy and cost saving (reduced cooling loads); are the other highlighted benefits of applying the shading device as a façade component. **It can be stated that the expanded metal mesh is contributing to sustainable architecture in an important way and this research investigated this behaviour of it through some of the significant parameters.**

However, in order to be able to present a more concrete discussion, a further analysis about the selected bestest cases have been made. Exploring how this optimization methodology is affecting the other problems related with the façade components, other than indoor illuminance comfort, is the final step of the research. This step would give a better idea about the real-life performance of the expanded metal mesh.

The Customized Spatial Daylight Autonomy analysis is seeking the comfort levels in an average value for the whole year which is very logical for this case were the expanded metal mesh is considered to be applied in a static way. However, the temperature and solar gain differences throughout the year, is unavoidable for most of the climates, especially the ones that this paper considers. That is why, for the detailed analysis related with the illuminance levels inside and the daylight glare probability; some of the significant days have been determined.

The important day have been found by analysing the epw file exported to excel. The dry bulb temperature for each climate is considered for this decision-making process. The first day which is explored is the average day which is supposed to be the temperature conditions that happens the most through the year, which makes is crucial to be considered. The second one is defined as the worst day that is considered to be the hottest one in terms of dry bulb temperature. The definition of "worst" is specific to this case, since days that a shading device is needed the most are the hottest days where the solar gains reaches its maximum.

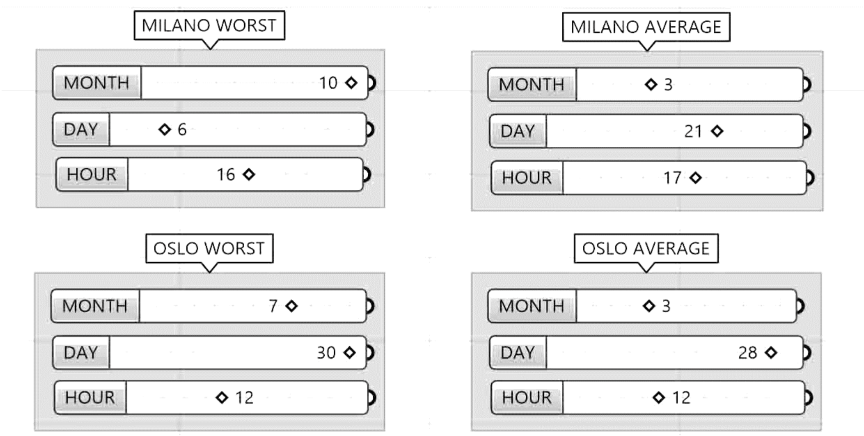
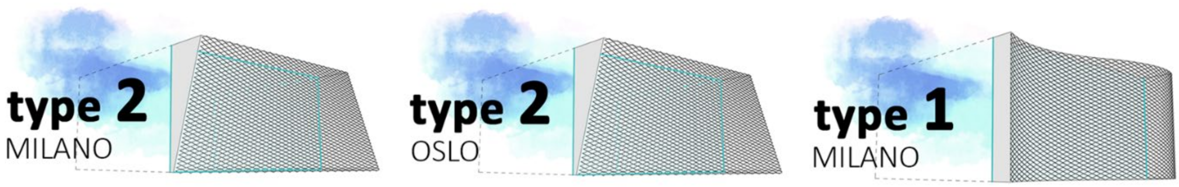


Figure 90: Screenshot from the Grasshopper script, represented the selected critical cases



FINAL ANALYSIS							
FURTHER SIMULATIONS	schedule of the simulation	SELECTED CHAMPIONS			NO EMM		
		TYPE 2, MILANO optimized	**TYPE 2, OSLO optimized**	**TYPE 1, MILANO optimized**	TYPE 2 OSLO	TYPE 2 MILANO	TYPE 1 MILANO
optimized CsDA	annual	70.23	51.78	69.01	30.95	47.61	43.26
Daylight Factor	annual	4.848	4.62	3.94	8.68	8.38	9.44
Average Illuminance [lux]	worst day	482.605	1092.94	380.42	1780.25	766.89	865.48
	average day	399.62	810.7	328.56	1337.49	677.39	744.71
Average Radiation [Wh/m2]	annual	69.86	79.09	60.54	142.06	133.32	157.97
Daylight Glare Probability	worst day	0.234	0.33501	0.329	0.33798	0.235	0.263
	average day	0.224	0.287	0.306	0.288	0.224	0.234
Average Annual Hourly Glare [hours]	annual	1.914	2.765	1.962	3.019	2.075	3.147

Table 14: Further analysis values, comparing the optimized results for the selected best cases and their versions without the EMM

Before going on with the detailed descriptions about the new ways of measurements; a summary of the results has been given with the chart above. All the analyses have not only been simulated for the bestest cases that are selected from the optimization process, but also to the variations on which the shading system has not been used at all, in order to perceive the improvements also for the further analysis. The problems that have been tried to be found out are; if the daylight glare probability, average annual hourly glare and daylight exceeds the required or suggested values with the optimized design, if the average radiation and the illuminance on critical days have been managed to be decreased. Moreover, the CsDA analyses have been made again, with the radiance parameters defined in a more accurate way. Since for the whole optimization process simplified values have been used for these parameters, it is crucial to check if these simplifications are acceptable.

14.1. CUSTOMIZED SPATIAL DAYLIGHT AUTONOMY comparison with radiance parameters

All of the customized spatial daylight autonomy analysis and the optimizations that are made in the methodology part are conducted for comparison purposed, which is why it was crucial to implement some simplifications in order to get fast and effective results. One of these important simplifications were the radiance parameters which is required to be connected to the simulation recipe of the honeybee daylight analysis component. However, to be able to save significantly from the time, this setting has been left with the default settings. This is a critical decision that might affect the results significantly but since it was a comparison analysis it was used in this way.

At this part of the research, the bestest configuration will be subjected to this accurate analysis where the more realistic results will be found and compared with the simplified ones to understand the range of errors.

The radiance parameters are used to define the resolution of the light that is hitting the surface of the analysis mesh. The higher the resolution is the more accurate the results would be. When you are analysing a complex surface that has a lot of detailed as the expanded metal mesh; it is suggested to have well-defined values for the radiance parameters that you make sure that each part of the shading is considered and effective. [44]

Here are the parameters that need to be defined offered by grasshopper; according to the necessities of the analysis;

- **Ab:** Number of ambient bounces. This is the maximum number of diffuse bounces computed by the indirect calculation. A value of zero implies no indirect calculation.
- **Ad:** Number of ambient divisions. The error in the Monte Carlo calculation of indirect illuminance will be inversely proportional to the square root of this number. A value of zero implies no indirect calculation.
- **As:** Number of ambient super-samples. Super-samples are applied only to the ambient divisions which show a significant change.
- **Ar:** Ambient resolution. "This number will determine the maximum density of ambient values used in interpolation. Error will start to increase on surfaces spaced closer than the scene size divided by the ambient resolution. The maximum ambient value density is the scene size times the ambient accuracy
- **Aa:** Ambient accuracy. This value will approximately equal the error from indirect illuminance interpolation. A value of zero implies no interpolation
- **Additional P:** Use this input to set other Radiance parameters as needed. You need to follow Radiance's standard syntax (e.g. -ps 1 -lw 0.01)

Here are the differences of the parameters between the default values that are used for the comparison part and the defined values that are used for an accurate analysis.

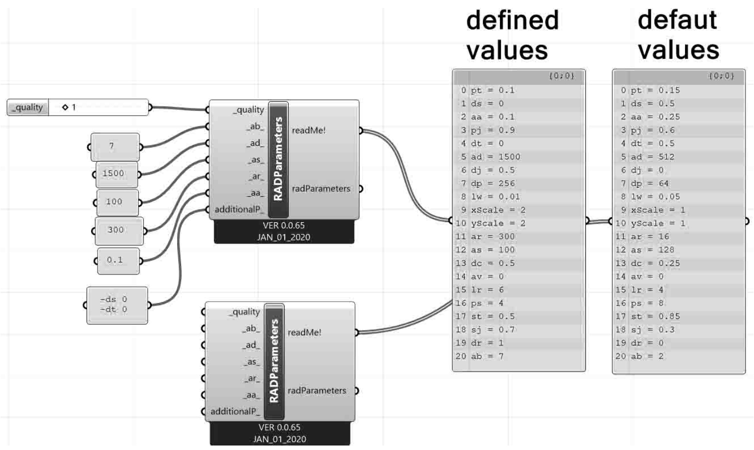


Figure 91: Screenshot from the Grasshopper script, representing the input comparisons for the radiance parameters

		TYPE 2, MILANO, optimized	TYPE 2, OSLO, optimized	OSLO	MILANO
optimized CsDA	annual	70.23	51.78	30.95	47.61
CsDA with Rad. Param	annual	62.5	46.42	20.83	42.26

Table 15: sDA results chart, representing the comparison values for the default and defined radiance parameter values

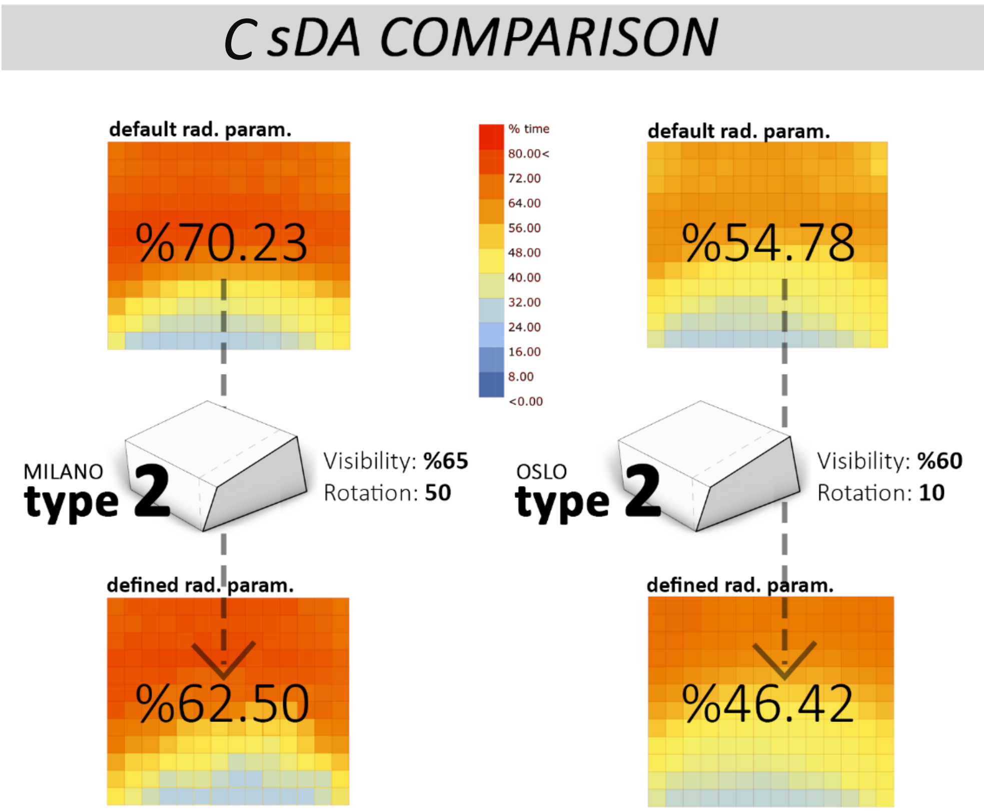


Figure 92 CsDA distribution on the analysis mesh results, representing the comparison values for the default and defined radiance parameter values

As it was predicted, the results are changing in a significant way, when the accurate radiance parameters are applied. For all of the trials, the actual values are lower than the assumed comparison values. However, the percentage of error is less than 10% which is acceptable to make a comparison. However, when making an in-depth analysis about the comfort of an expanded metal mesh shading design on an actual project to be built, it is suggested to use the accurate values.

14.2. DAYLIGHT FACTOR

Daylight factor is the measure of the amount of illumination available indoors relative to the illuminance present outdoors at the same time under overcast skies.

$$daylight\ factor = \frac{inside\ illuminance}{outside\ illuminance} * 100$$

This value is independent from the building site and the time of the day of analysis which actually are key design parameters. This fact leads to two sources of uncertainty to predict indoor illuminance that are the fluctuation in the total amount of light penetrating a cloudy atmosphere and the fluctuation in the sky's brightness pattern. It is best considered as an indicator of the performance of the room when the sky is overcast. Below, the ranges that represent the best conditions and the ones that indicate discomfort are listed. The aim is to be between 2% and 5% for the optimized cases. [2]

- <2% - GLOOMY
- 2%<DF<5% - BEST CONDITION
- >5% - OVER-LIT

The analysis is made with Honeybee and ladybug, supported by Grasshopper. The daylight factor is calculated for each square of the grid of the analysis mesh in order to understand the distribution. Then the average of these values is calculated to have a general idea about the comparison between the optimized case and the non-shading case. Here is the script that is used for this simulation.

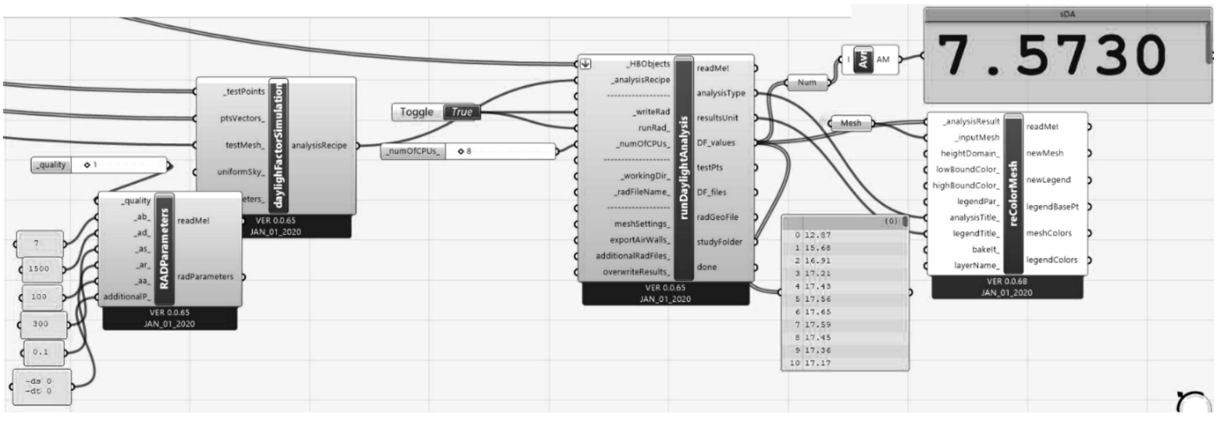


Figure 93: Screenshot from the Grasshopper script, showing the daylight factor calculation path

The daylight factor calculated for the configurations without the shading device had gave very bad results by being above 5% which indicated that the over-lit areas are dominating the room and creating discomfort. Thanks to the shading system that is implemented to the models; the daylight factor value has been decreased to the range of comfort for all of the configurations and climates, which is shows the effectiveness of the system. The daylight factor distributions inside room are represented with the coloured meshes below, in comparison to the initial results.

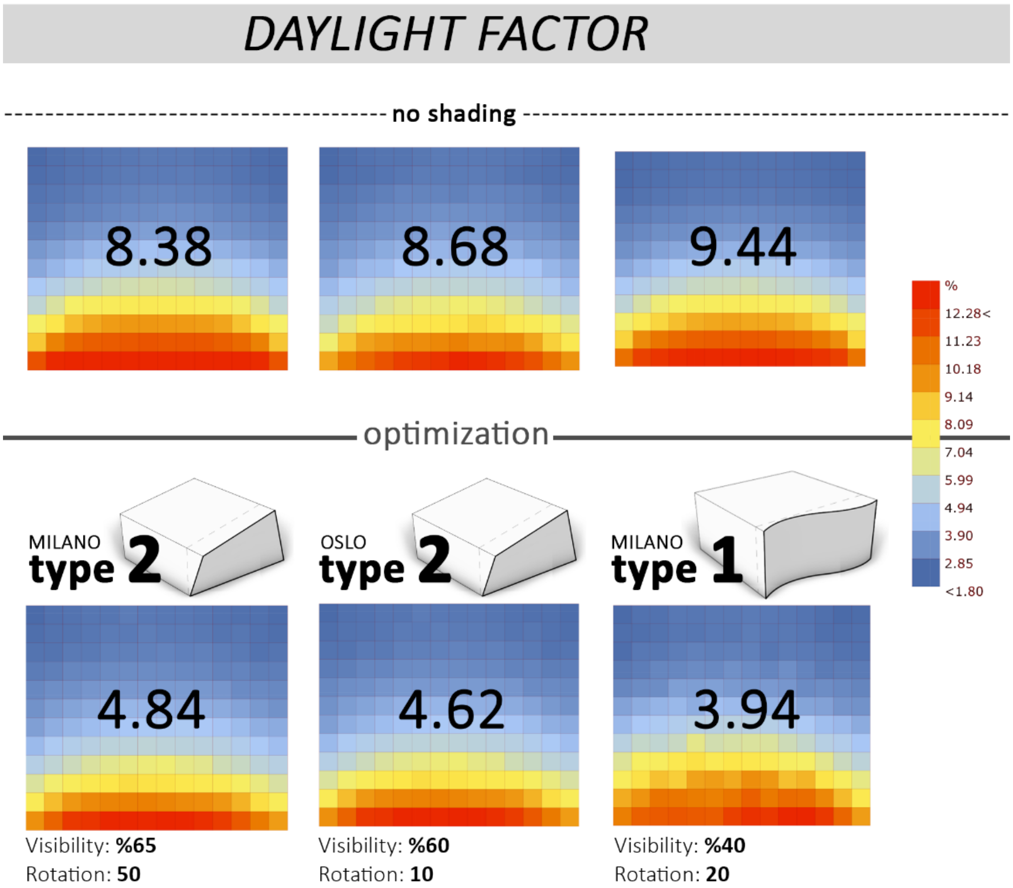


Figure 94: Daylight Factor results inside the subjected spaces, comparing the best configurations with their no EMM applied version

14.3. AVERAGE ANNUAL RADIATION

Solar radiation, often called the solar resource or just sunlight, is a general term for the electromagnetic radiation emitted by the sun. Solar radiation can be captured and turned into useful forms of energy, such as heat and electricity, using a variety of technologies. However, the technical feasibility and economical operation of these technologies at a specific location depends on the available solar resource. [33] The units of measure are Watts per square meter. Every location on Earth receives sunlight at least part of the year. The amount of solar radiation that reaches any one spot on the Earth's surface varies according to:

- Geographic location
- Time of day
- Season
- Local landscape
- Local weather

Sunlight is a portion of the electromagnetic radiation given off by the Sun, in particular infrared, visible, and ultraviolet light. On Earth, sunlight is scattered and filtered through Earth's atmosphere, and is obvious as daylight when the Sun is above the horizon. When direct solar radiation is not blocked by clouds, it is experienced as sunshine, a combination of bright light and radiant heat. When blocked by clouds or reflected off other objects, sunlight is diffused. Sources indicate an "Average over the entire earth" of "164 Watts per square meter over a 24-hour day" [32]

As EM is a metal product, one might be worried about the temperature it could reach under solar radiation and the subsequent radiative effect. As an initial benefit, EM will very often reflect radiation upwards, avoiding heat transfer to the ground. We have to consider the effect of colour and finish but, in general, EM shadings do not reach very high temperatures, probably due to the high proportion of voids and its easy ventilation.

Radiation is one of the most important factors that is affecting the comfort inside. That is why, it was necessary to observe if the adequate decrease by the help of the shading device is reached or not for the bestest configurations. Below, the comparison of the annual average radiation results are represented, and the results are showing that the shading system is decreasing the Wh/m^2 value almost to the half for all the cases.

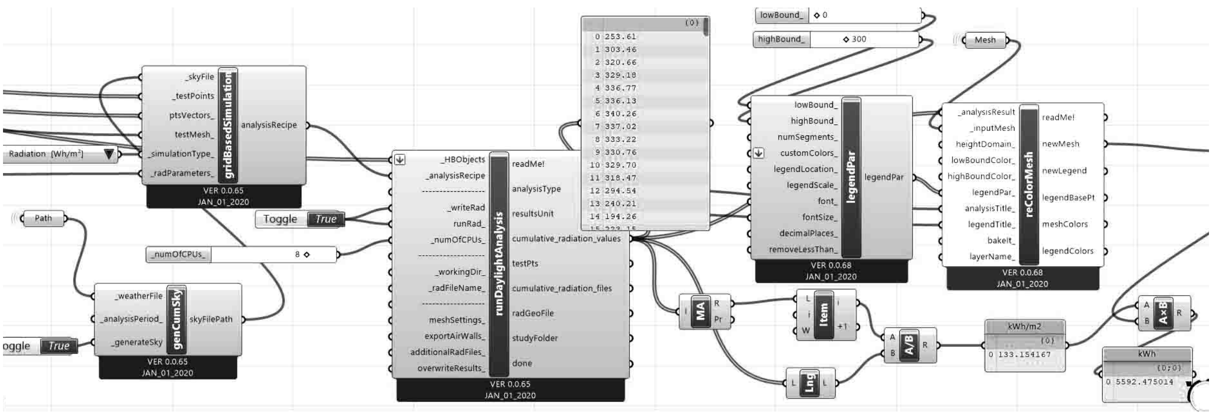


Figure 95: Screenshot from the Grasshopper script, showing the annual average radiation calculation path

This calculation is made as an annual average calculation from Honeybee. The script that is made for this simulation is shown in the screenshot above.

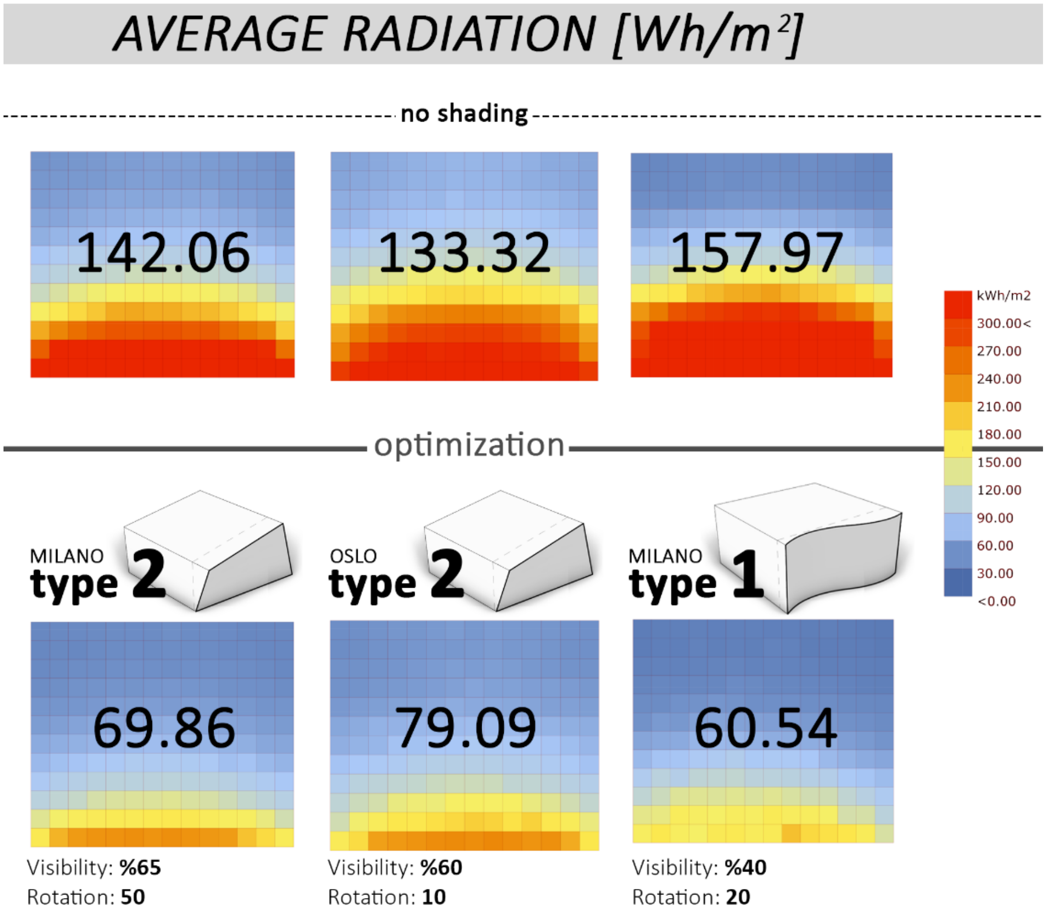


Figure 96: Annual average radiation results inside the subjected spaces, comparing the best configurations with their no EMM applied version

14.4. THE PROBLEM OF GLARE

Glare is the loss of visual performance or discomfort produced by an intensity of light in the visual field greater than the intensity of light to which the eyes are adapted. Moreover, glare occurs when too much light enters your eye and interferes with your eye's ability to manage it. Glare can be distracting and even dangerous and can occur day or night in a number of ways. Glare may come directly from a light source or be reflected. There are four types of glare: Distracting glare, discomforting glare, disabling glare, and blinding glare. [42]

Another problem to address with shading devices is the appearance of discomfort glare, related to the presence in the visual field of excess luminance differences (Perry, 1990). In urban environments, façade glare affects visual comfort (discomfort glare) and influences the thermal load of other buildings (solar radiation from more than one source) (Brzeski, 2012). In most buildings, glare protection is necessary to maintain proper visual comfort. In order to have an idea about the discomfort that glare might create inside the buildings; a range of indication is determined that shows if the glare levels inside the building is disturbing or perceptible. This range is presented below.

Daylight Glare Probability

- DGP<0.35 – IMPERCEPTIBLE
- 0.35<DGP<0.40 – PERCEPTIBLE
- 0.40<DGP<0.45 – DISTURBING
- DGP>0.45 - INTOLERABLE

The aim to be achieved by the shading system is to have the daylight glare probability below 0.40 so that the visual comfort inside the space is sufficient. The DGP calculation is made from a certain point of view that is determined by the user. In order to find an approximate value for the room, the viewpoint for the simulations have been set up to be in the middle of the analysis mesh. The calculated DGP values that are listed below shows that the values are in the desired range for all the cases. [48]

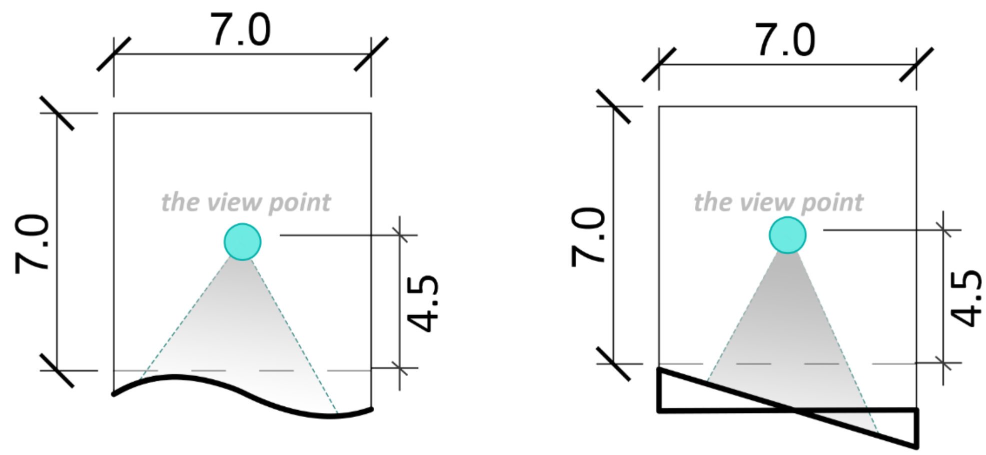


Figure 97: The viewpoint diagram of the glare analysis

schedule of the simulation	CONFIGURATIONS			NO EMM		
	TYPE 2, MILANO, optimized	**TYPE 2, OSLO, optimized**	**TYPE 1, MILANO, optimized**	TYPE 2 OSLO	TYPE 2 MILANO	TYPE 1 MILANO
worst day	0.234	0.33501	0.329	0.337	0.235	0.263
average day	0.224	0.287	0.306	0.288	0.224	0.234

Table 16: Daylight Glare Probability results, comparing the best cases with their versions without having EMM applied, for the worst and the average day

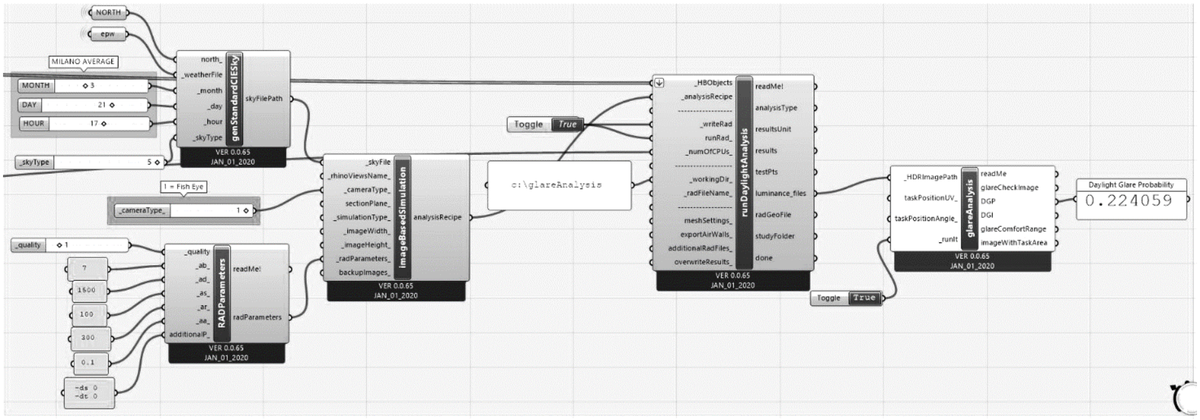


Figure 98: Screenshot from the Grasshopper script, showing the daylight glare probability calculation path

Annual Glare Average Hours

The average hours glare throughout the year has also been calculated to make sure that it is not above 4 hours which indicated unacceptable levels. It is important to make this simulation because the daylight glare probability value only give a general idea about the space without considering the defined test points, while for this analysis the simulation is made for each test point and the average is taken. So, it is also possible to see the distribution inside the space and which areas are critical for glare. [40]

- 0 hours – BEST CONDITION
- 1-3 hours – ACCEPTABLE
- Above 4 hours - UNACCEPTABLE

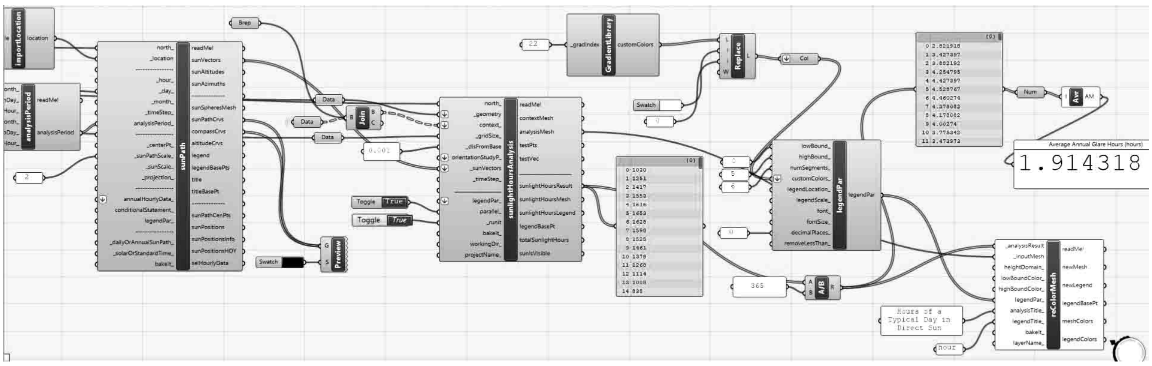


Figure 99: Screenshot from the Grasshopper script, showing the annual average glare hours calculation path

Above, grasshopper script that is made using the Honeybee components are shown, Moreover, the room distribution results are shown below in a graphic way. As it is clear, before shading devices were applied the annual average glare hours were in the critical range for discomfort. However, with the optimized configuration it is managed to be decreased significantly. Moreover, the predictable result that the problematic areas to be near the glazing is also confirmed.

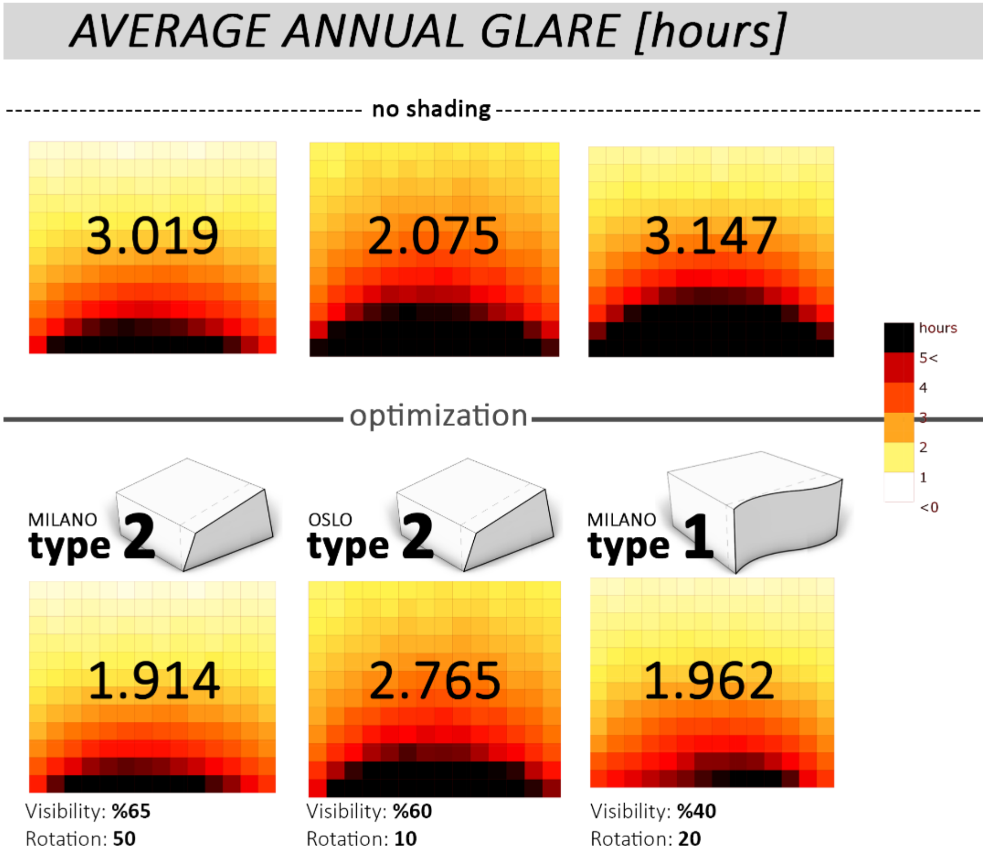


Figure 100: Annual average glare hour results inside the subjected spaces, comparing the best configurations with their no EMM applied version

14.5. AVERAGE ILLUMINANCE

In photometry, illuminance is the total luminous flux incident on a surface, per unit area. It is a measure of how much the incident light illuminates the surface, wavelength-weighted by the luminosity function to correlate with human brightness perception. Similarly, luminous emittance is the luminous flux per unit area emitted from a surface. Luminous emittance is also known as luminous exitance. In SI derived units these are measured in lux (lx), or equivalently in lumens per square metre ($lm \cdot m^{-2}$). In the CGS system, the unit of illuminance is the phot, which is equal to 10000 lux. The foot-candle is a non-metric unit of illuminance that is used in photography. [49]

Illuminance was formerly often called brightness, but this leads to confusion with other uses of the word, such as to mean luminance. "Brightness" should never be used for quantitative description, but only for nonquantitative references to physiological sensations and perceptions of light.

Generally, factors that affect the effectiveness of illumination are quantity and quality of light, amount of flicker, amount of glare, contrast, and shadows. Each factor must be adjusted differently to optimize illumination in emergency, safety, operations, and security situations, for instance. Lighting Standards also serve to address the plethora of other concerns associated with the design, placement, installation, and minimum energy requirements and efficient allocation of illumination in different locations with different purposes, as well as the efficiency, durability, cost, and maintainability. [33]

The calculation of illuminance is one of the most important indicators of daylight design. The outdoor light level is approximately 10,000 lux on a clear day. In the building, in the area closest to windows, the light level may be reduced to approximately 1,000 lux. In the middle area it is may be as low as 25 - 50 lux. Additional lighting equipment is often necessary to compensate the low levels. Earlier it was common with light levels in the range 100 - 300 lux for normal activities. Today the light level is more common in the range 500 - 1000 lux - depending on activity. For precision and detailed works, the light level may even approach 1500 - 2000 lux.

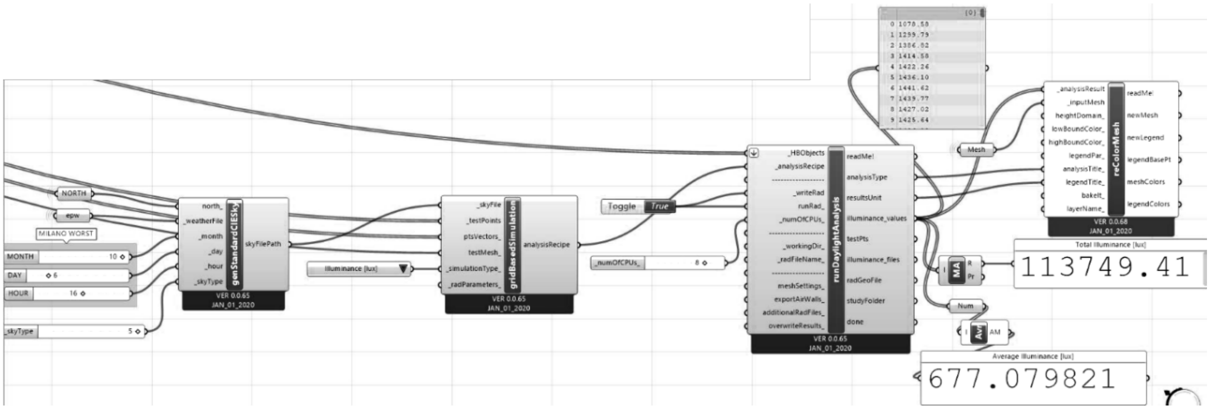


Figure 101: Screenshot from the Grasshopper script, showing the average illuminance for critical days calculation path

The customized spatial daylight autonomy already considers the illuminance values as its reference to define the daylight comfort on the test points, according to the range that is set up as acceptable. However, it is only showing for how much of the time we are in this range. Even though it is a good indication of general comfort, it is also crucial to see the real illuminance levels inside. Also, because the comfort range that is defined is between 300 and 2000 lux which is highly wide range. That is why it is interesting to calculate the actual average illuminance inside the space to see around which level the design is taking it.

The calculation is made for the critical days for both of the climates; Oslo and Milano. The dates which are used are the same ones as shown before, both for the worst and the average day. The day, month and hour are connected to the CIE sky component and the analysis is made with the script shown above.

Below, the tables are shown for both of the critical days; if the optimized cases have illuminance values are in the range of comfort and how the results are changing compared to the case without the shading.

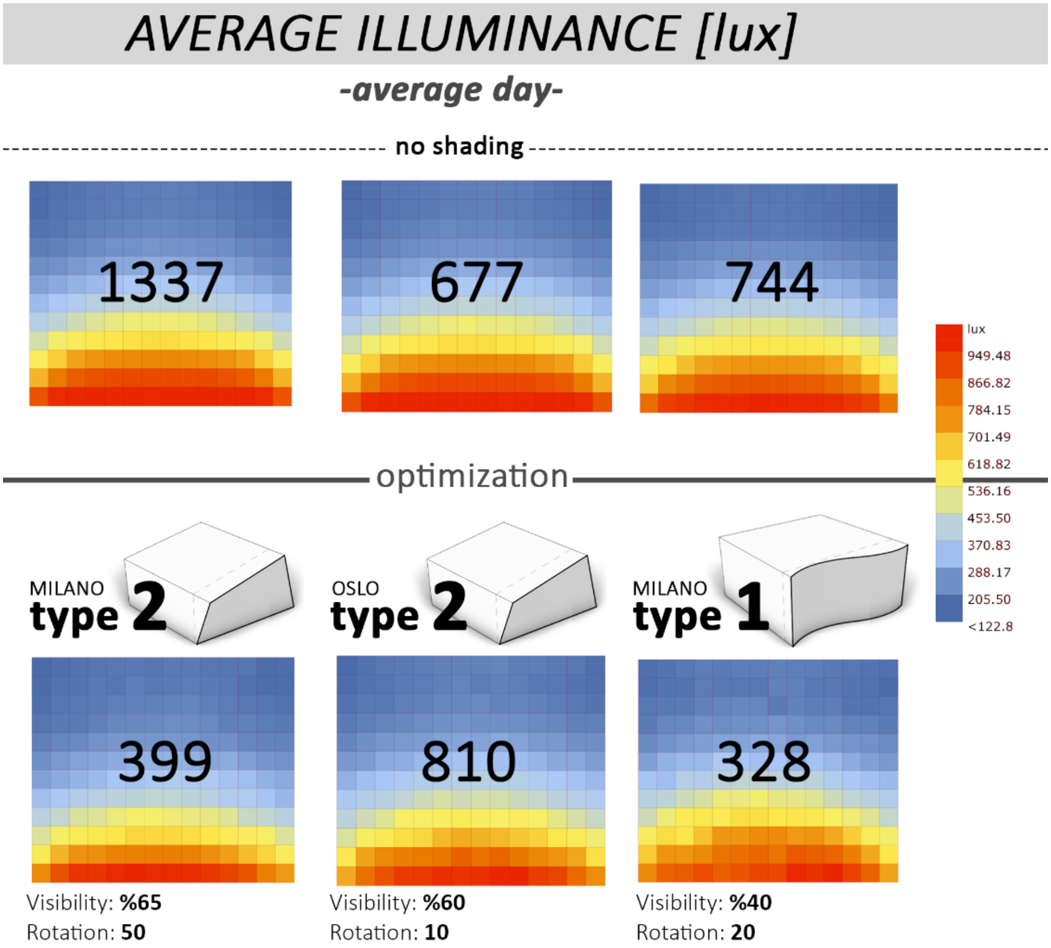


Figure 102: Average illuminance results for the average day inside the subjected spaces, comparing the best configurations with their no EMM applied version

The illuminance results for both of the cases are always within the range of defined comfort. However, it is surprising to see that it is also confirmed for the cases without any shading device. This is showing the dominancy of the under-lit areas caused by the depth of the space. It is true that the problem of glare and the discomfort cause by the over-lit spaces have been improved by the expanded metal mesh; however, shouldn't be forgotten that artificial lightings must be applied to solve the problem of under-lit areas.

There should be a compensation between the cooling loads and the electrical energy loads. For the case of this research, it was focused intensely on the effect of shading which is related with the reduction of cooling loads. For the further studies it might be useful and interesting to be working on this issue of balance as well.

As a last comment about illuminance, it can be stated that the best results are again obtained by the second typology since the values are closer to the medium of the range.

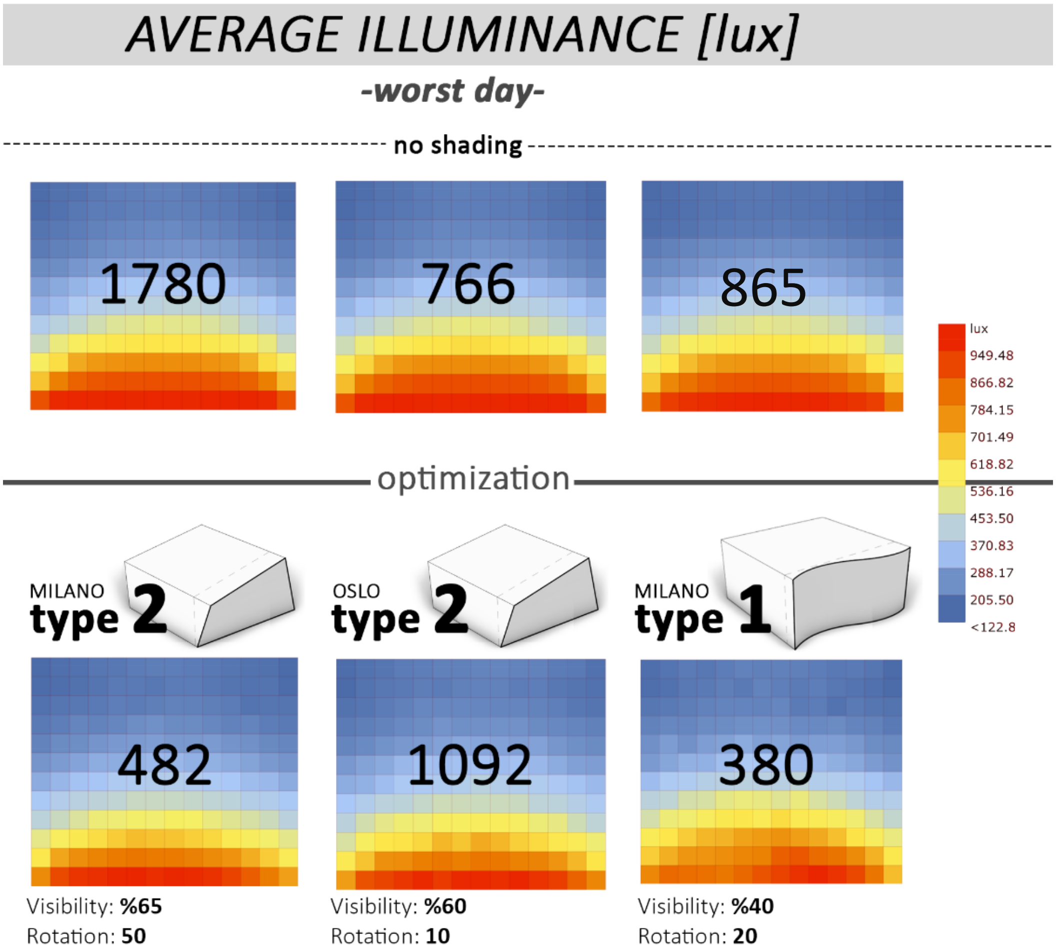


Figure 103: Average illuminance results for the worst day inside the subjected spaces, comparing the best configurations with their no EMM applied version

15. *Final Optimization for the Best Cases*

The final step for the optimization process has been the decision of adding the annual average radiation as the second output. It is considered to be the updated version for the methodology where not only the Customized Spatial Daylight Autonomy is optimized by maximizing the value, but also the annual average radiation is optimized by minimizing the value. The annual average radiation value is calculated for the whole year considering the night-time as well. Octopus has been used again, having the same parameter definitions; the visibility percentage and the rotation of the strips. However, the range of the visibility percentage has been changed due to the previous results of the analyses that showed that after 65%, the shading impact of the expanded metal mesh was decreasing significantly. Decreasing the possible parameter values has made is possible to get better and more accurate results within shorter periods of analysis time. Moreover, adding the radiation as the “fitness” value for Octopus, gave the chance to control the comfort inside the building while managing the solar radiation as well.

The summary of the results is represented with the excel chart below, where the CsDA and the radiation values are compared with the previous optimization process, as well as the configuration without any shading device.

		RADIATION [Wh/m2]	CsDA	*visibility percentage*	*rotation of the strips*
TYPE 2 MILANO	NO EMM	133.32	47.61	-	-
	CsDA Optimization	69.86	70.23	65	50
	CsDA and Radiation Optimization	**34.2**	**83.92**	**50**	**60**
TYPE 2 OSLO	NO EMM	142.06	30.95	-	-
	CsDA Optimization	79.09	51.78	60	10
	CsDA and Radiation Optimization	**48.43**	**64.88**	**40**	**15**
TYPE 1 MILANO	NO EMM	157.97	43.26	-	-
	CsDA Optimization	60.54	69.01	40	20
	CsDA and Radiation Optimization	**48.49**	**70.83**	**45**	**10**

Table 17: Description of the evolvement of CsDA and annual average radiation through the optimization processes

The models that were used for the final step were, again, the bestest configurations found from the first optimization process. Since they already gave effective improvements by the application of the expanded metal mesh, it was aimed to observe if the addition of radiation as the new optimization goal would be able to increase the comfort even further. To be able compare these changes, the same inputs for the shoebox model are used. (material properties, shoebox size and orientation). The comfort range for the CsDA analysis has been kept the same (300 lux-2000lux) too. The only difference of the process was the management of the results of the optimization. Before, the possible results coming from the trial that Octopus made by changing the geometrical parameters, were listed with point on the linear line. However, with the updated script, it was necessary to have a 2-dimensional result were the pareto curve is created where only one of the points on the curve indicates the best-balanced results for both outputs. The other trials are placed outside the curve, since the program recognizes the better one and eliminates the ones that cannot exceed that.

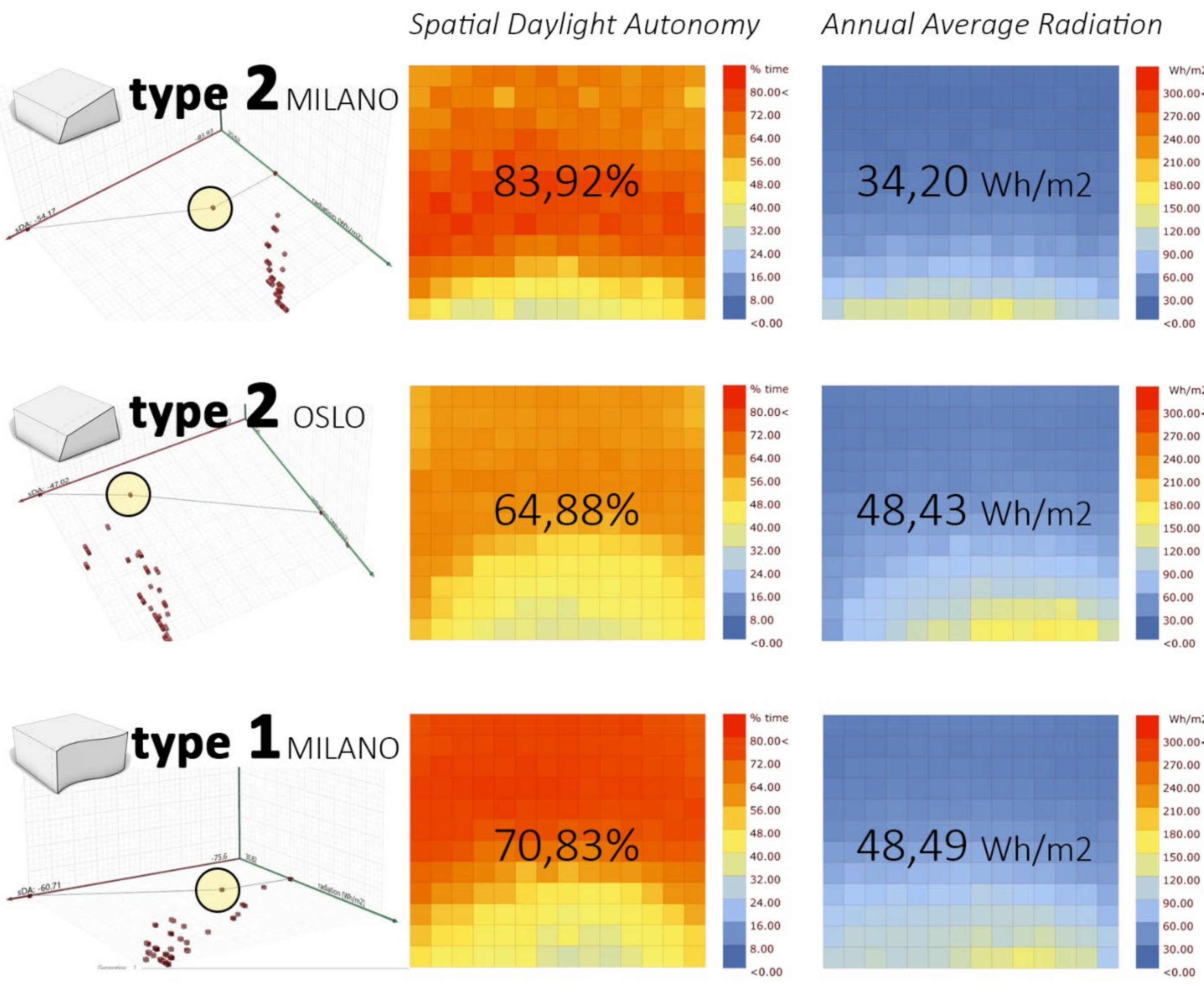


Figure 104: The distribution of the CsDA and radiation on the optimized analysis models and the screenshot from the octopus pareto curve

The optimization was kept running for 20 hours for each case and it was perceived that decreasing the visibility percentage had given a better chance for Octopus to find a better solution. For all the 3 cases, not only the radiation is decreased significantly, the CsDA was managed to increase even more than the first optimization. The distribution of the results on the analysis mesh have been summarized above. Moreover, in order to observe the improvements that were achieved in every step of the process, the diagrams below have been created. Both the improvements, and the detailed description of the final design of expanded metal applied of bestest surface configuration are represented by the drawings.

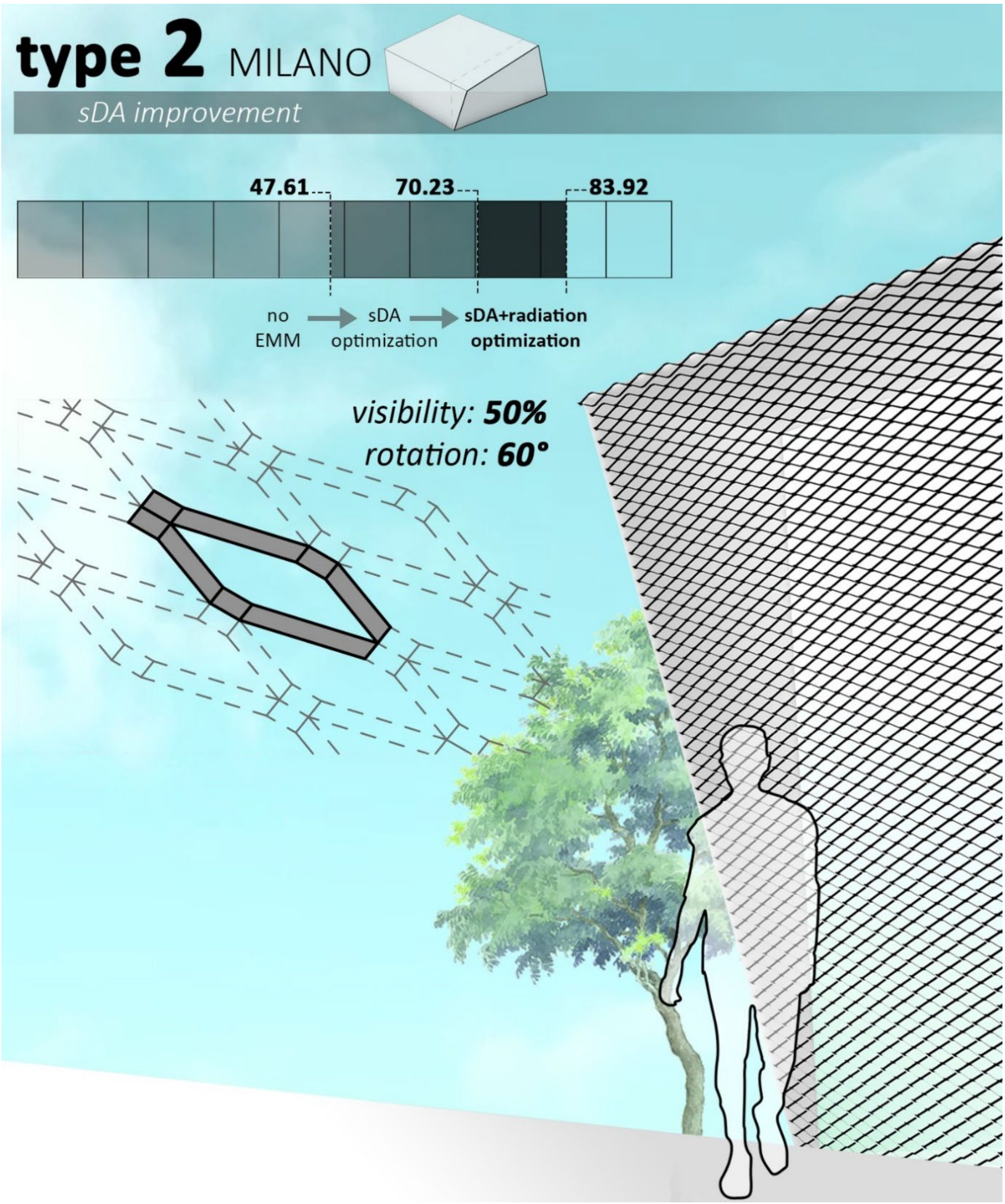


Figure 105: Final description of the parameters and optimized values of TYPE 2 Milano, Credits belong to the author

The Type 2, Milano configuration had showed the best improvements for the CsDA. The final value that is achieved is 83,92% which is showing that the daylight comfort inside the room is managed for the majority time of the year. The visibility percentage have changed from 65% to 50% while the rotation of the strips changed from 50 degrees to 60 degrees. This result is showing that in order to decrease the solar radiation coming inside, it is better to use lower values of visibility which consequently increase the daylight comfort. The angle being 60 degrees is indicating that the solar incidents coming from west due to the form of the surface, is also critical for Milano climate and that this characteristic of the expanded metal mesh is giving the possibility to control this impact.

As for the TYPE 2 configuration in Oslo, the visibility percentage becomes 40% (previously 60%) while the rotation becomes 15 degrees (previously 10) which shows the effectiveness of the new updated methodology as well as the different impact on the climates. There was a significant increase on the CsDA thanks to the decrease in the size of the holes, avoiding the higher amounts of solar radiation coming inside.

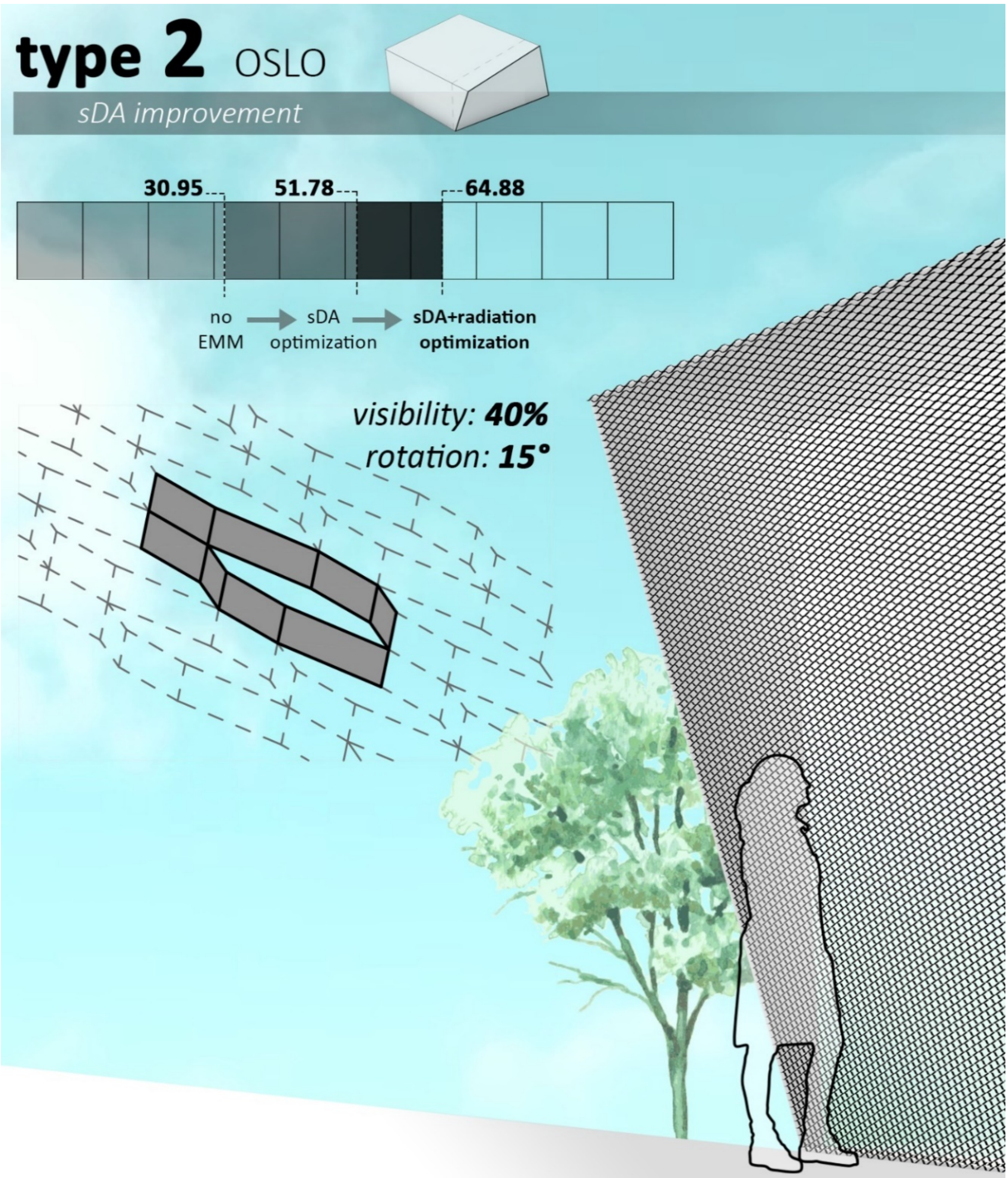


Figure 106: Final description of the parameters and optimized values of TYPE 2 Oslo, Credits belong to the author

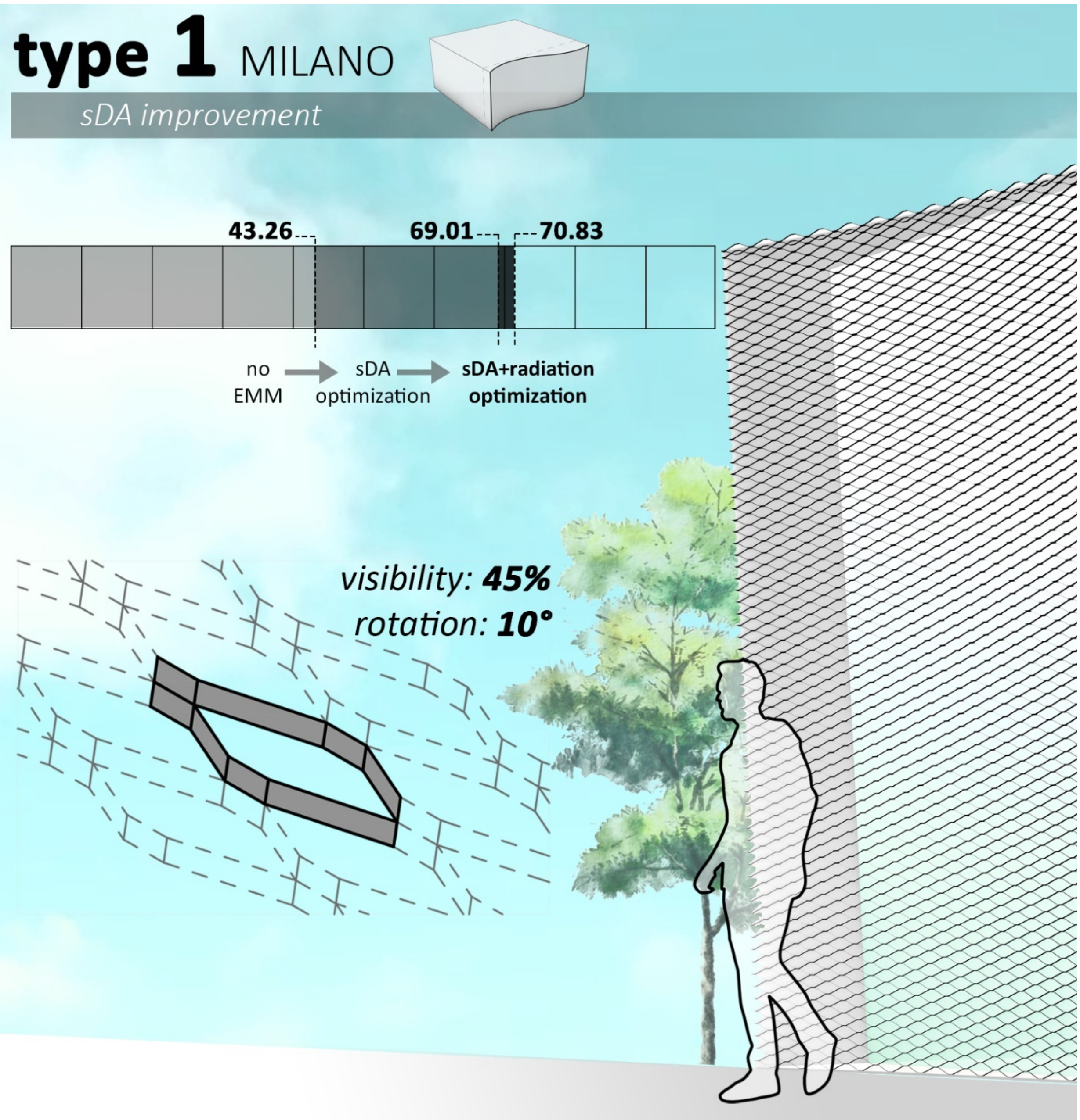


Figure 107: Final description of the parameters and optimized values of TYPE 1 Milano, Credits belong to the author

The final analysed configuration was the TYPE 1, Milano case; which showed the lowest amount of impact dure to the fact that as a result of the first process, the 40% of visibility was found by Octopus. However, the outputs are further optimized by changing the geometrical parameters without any significant difference.

Thanks to this final step, it was managed to improve the daylight comfort further, which is the main goal of the whole process. However, it is also understood that the optimization methodology works better and better as the behaviour of the material is understood further, hence, adding well-defined limitations. It was satisfactory that, after all the attempts of exploiting the characteristics of expanded metal mesh to increase daylight comfort, each step that is taken had demonstrated useful data to move forward. In the end, the all the selected cases have managed to have an efficient daylight performance.

DISCUSSION

The main goal of this research was to understand, analyse and optimize the geometrical parameters of the expanded metal mesh with regards to its daylight performance. The material has been realized in depth within its areas of usages, as well as its behaviour when it is applied on a building façade as an exterior cladding component. The shading effect was the key point of the whole process. Increasing the daylight comfort inside the space of a building by exploiting the parameters has been the critical goal upon which all the decision is made.

To understand the daylight behaviour of the complex geometry of expanded metal mesh; a comparison methodology has been used. The comparisons have been made in terms of; the climate, orientation, shoebox model sizes, case study building, different surface typologies and between configuration with optimized parameters of expanded metal mesh and without any applied shading system. Since many aspects have been considered, significant simplifications have to be made to balance the timing of the process and the necessary outputs to build the research upon.

In the end, the results obtained for the optimized expanded metal mesh gave significant improvements and it was proven that the methodology was working. However, due to these simplified approaches; some of the decisions were left premature and further studies are suggested to be made about them.

The first and the most important simplification was made on the decision of how to control the geometrical parameters, while expanded metal mesh had many different ways to be controlled. Shape of the holes, sheet thickness, strands, bonds, short way distance, long way distance, strand thickness, strand width, density of openings and colour were the main geometrical parameters that were defined by the producer companies. However, it was decided to decrease them into a strategically controlled parameters where the rotation of the strips and the size of the holes were the key factors.

A simplified way of controlling these important variables have been found by fixing the strip thickness as a constant value and changing the rotation of the strips and the hole size to be able to optimize the mesh. The limitation of these values is implemented according to documents obtained by the production companies. Moreover, an average factor value has been found between the long way distance and the short way distance of the holes and the parameter has been managed to be controlled by one value that is making hole size change proportionally. The definition of the hole size is converted into visibility percentage.

Within these defined ranges of the parameter, there were results that were able to optimize the behaviour of the expanded metal mesh. However, it should be stated that the simplification did not work for a part of the range.

Starting with the parameter "**ROTATION OF THE STRIPS**", it is clear from the results that the defined geometrical range was working well since the impact of changing the angle was significant. The further study that should be made for this case would be the fact that the varying the rotation of the strip is only functioning when the expanded metal mesh was applied on the south façade.

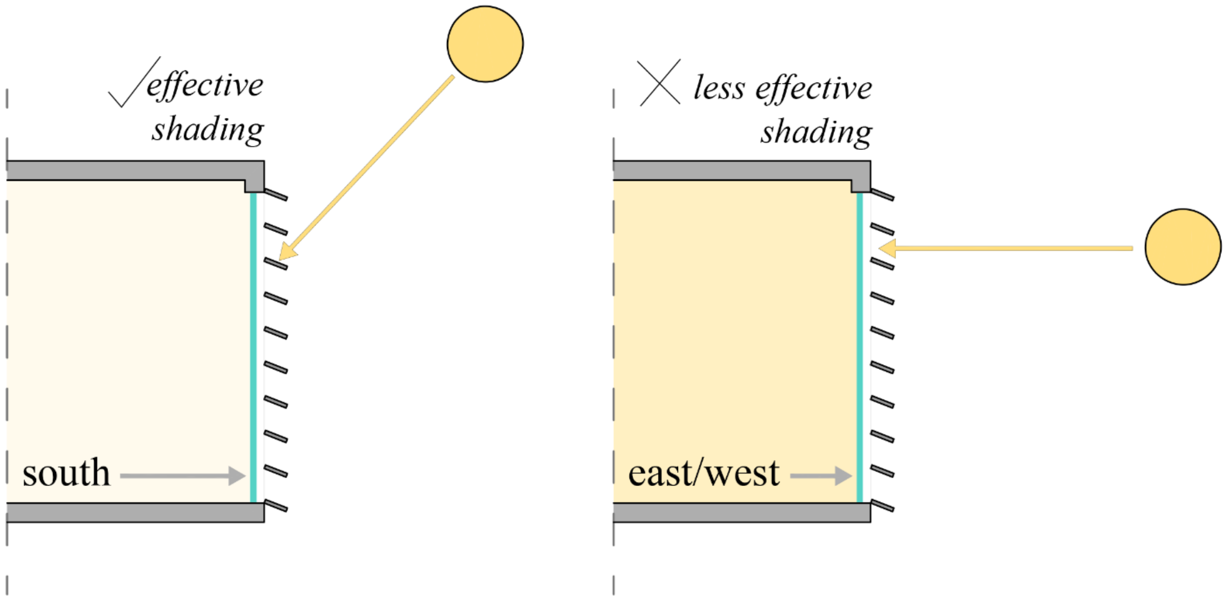


Figure 108: Diagram representing the different impact of EMM on orientations, Credits belong to the author

The mesh had always been applied on a subjected model in a horizontal way which leads the properties to control the daylight only for the south façade on which the sun angle is perfect to be avoided. While for the east and west façade, where the daylight comfort should also be managed, the methodology did not work very well. A further study on defining the placement of the mesh in different directions would be highly useful to be able to exploit the properties of expanded metal mesh in a better way.

The second and highly important subject of discussion is the simplified parameter, "**VISIBILITY PERCENTAGE**". As mentioned, the script has been written in such a way that, while the visibility percentage changes along with the hole size; (the limitations were decided according to the production references) the thickness of the strip remains the same. This was a good approximation in the beginning, however, after finalizing all the simulations it was observed that after 65% of visibility, the shading impact of the expanded mesh was decreasing significantly and for the higher values it was not working as a shading device at all.

This is due to the decision about keeping the strip thickness the same. For the real usages of the expanded metal mesh, the hole size and the strip thickness have an undefined proportion between them. Even though higher values of the hole are producible, the strip thickness should go hand in hand with it so that the shading impact is not lost.

For all the models of optimization, including the flat shoebox analysis, five case study buildings, and three designed surface typologies, the best values for the visibility percentage were below 65%, showing the ineffectiveness of the higher ones. **It would be very interesting to include the thickness of the strips into this optimization process for the further studies and offer a better methodology that architects and engineers can use to design expanded metal mesh as a shading device.**

The image below is showing the range of visibility that is used for the analyses and their efficiency in terms of having an impact on the daylight comfort as a shading device.

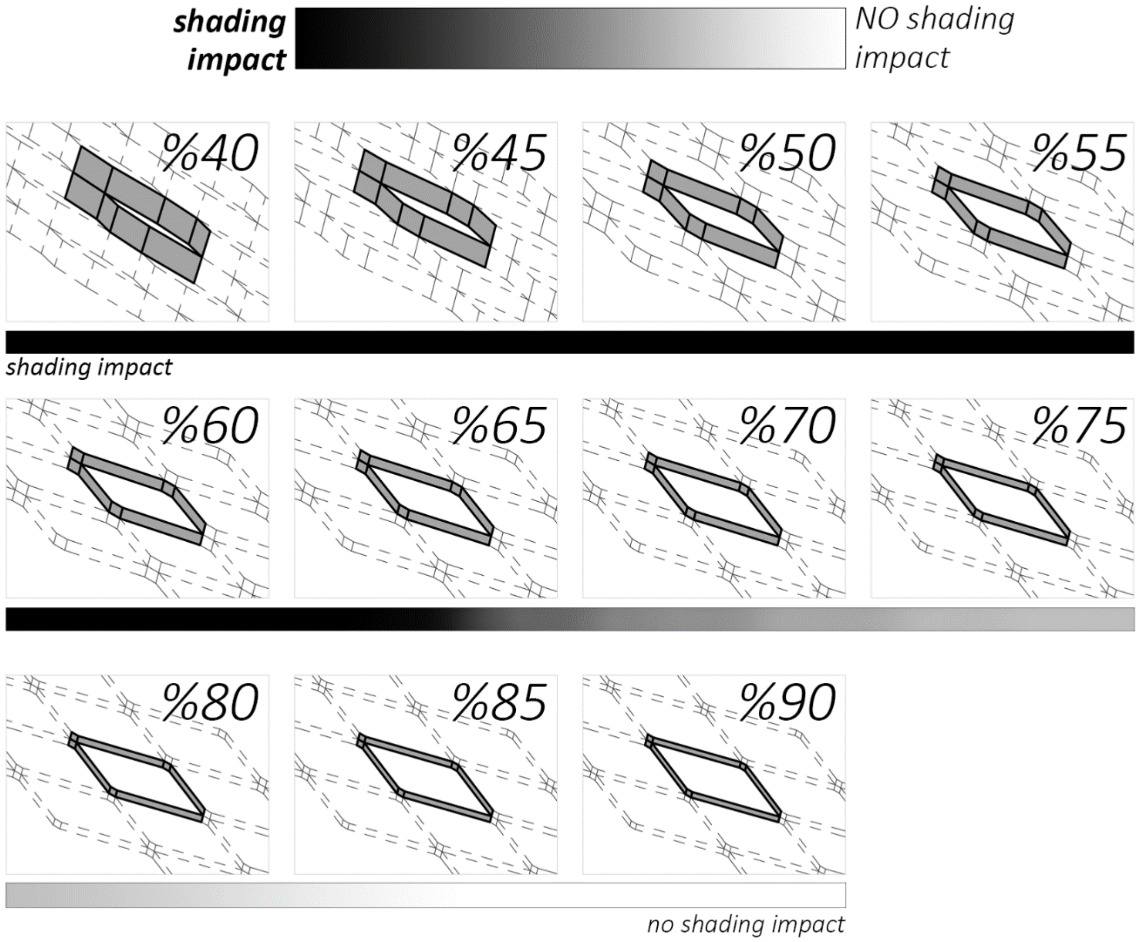
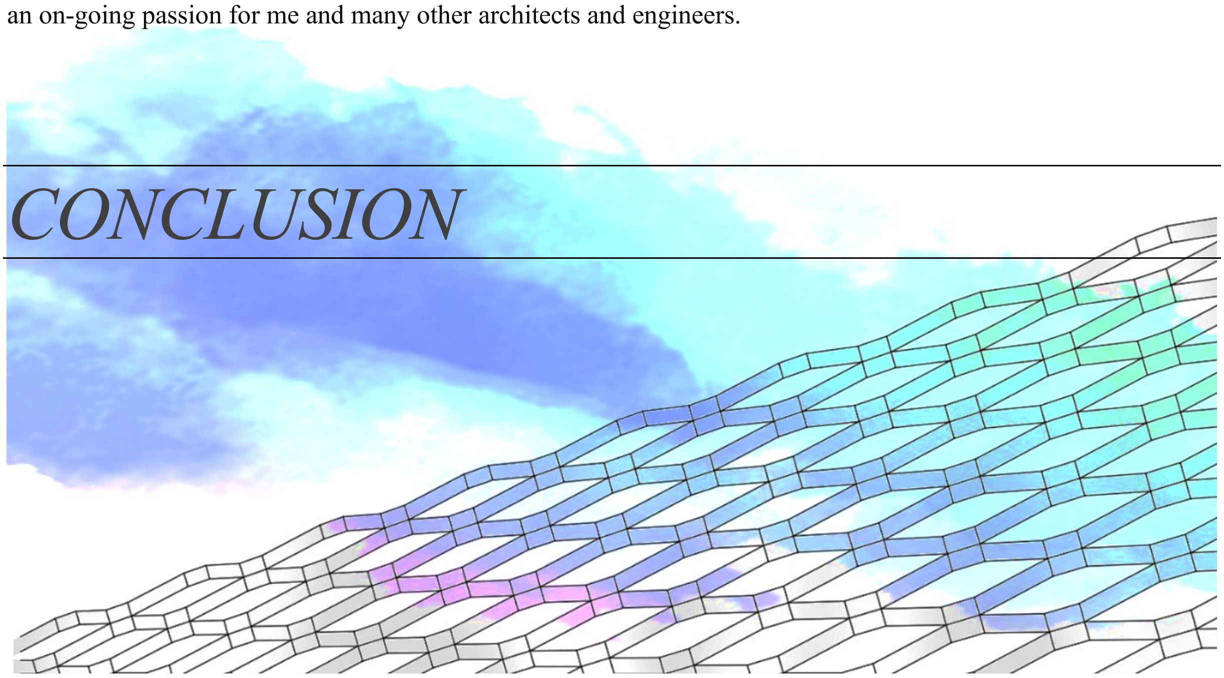


Figure 109: Diagram of the possible visibility percentage configuration, indicating their effectiveness as a shading device, Credits belong to the author

The matter that I would like to point out for the further studies would be related with the measurement of the analysis. It was discussed before the reason why customized spatial daylight autonomy which indicated the comfort levels in terms of illuminance inside a space. Moreover, the values used for the comparison were efficient enough to select the best cases that, the final in-depth analysis had given sufficient results. However, after finishing this whole process of optimization I realized that the results that were being compared were affected by the under-lit areas in a too dominant way. While the main objective of this research was to optimize the shading effect of the expanded metal mesh; it would have been interesting to observe the results in a more focused way. Another research on the performance of expanded metal mesh has been made using the daylight transmittance as the method of assessment, which gave highly accurate results. I believe it would be very useful if the daylight transmittance value is investigated for all the cases that are analysed in this research, for further studies.

I believe in the world of building optimization, especially using the parametric modelling tools, there is not only one answer. Critical decisions and simplifications have to made in order to obtain the answers that are specific to the problem. That is why, I would like to state that, I have manage to get compelling answers to all my questions in the beginning but at the same time new challenging questions have emerged which makes this field of research an on-going passion for me and many other architects and engineers.

CONCLUSION



The thesis had investigated certain aspect of expanded metal mesh as a shading device in order to find a way to improve the daylight design of a building and support the sustainable architecture methodologies in from an optimization point of view. The importance of building envelope components has been stated in terms of providing sufficient daylight inside while avoiding the over-heating and excessive solar gains. A computational way of preventing these problems while providing an effective shading to the interior spaces of the building have been studied.

The primary analyses have indicated that the geometrical parameters of expanded metal mesh can be simplified in such a way that the daylight performance of it can be managed in a controlled way. The visibility percentage and the rotation of the strips have been selected as the most significant geometrical characteristics of EMM and they are parametrized within the production limitations. The changes that each extreme configuration made out of defined values for the parameters showed that it was possible to have an impact on the daylight comfort.

The clear understanding of the impacts of the material characteristics, created the baseline for the optimization processes. The optimization using the plug-in Octopus, supported by Grasshopper, is made in order to exploit these properties as much as possible and increase the customized Spatial Daylight Autonomy value as much as possible, to provide the daylight comfort on which the expanded metal mesh is applied. The first optimization has been made for a simple flat shoebox model located in Oslo and Milano, for the south façade. South façade was selected a critical orientation input, due to the geometry of the material that is able to block solar radiation coming from a higher angle. The primary analysis has found sufficient values for the parameters that the CsDA value was increased significantly. The second important step was to prove that the application of EMM on real building façades was an effective design decision. This investigation was also made by using the same optimization methodology to find out the best results. Thus, for 4 out of 5 cases the methodology was proven to be working in terms of daylight comfort.

The next section of the research was proposing a methodology to adapt the mesh to different typologies of complex surfaces and apply the optimization procedure to those surfaces on which the geometry is implemented. A single degree curvature surface, a double degree curvature surface and lastly a dome type surface have been modelled and combined with the shoebox model. The application has been conducted using the computational tools by moving the smallest module of the expanded metal mesh on to points that are obtained by the controlled grid on each surface, transforming the normal vectors. The geometrical parameters were implemented in a adequate way that the optimization process had been successful for most of the cases. The CsDA value has been increase significantly for the models which have a better surface geometry in terms of managing daylight and the best results have been given with the lowest values of visibility percentage and values closer to 45 degrees for the rotation of the strips. This process gave a clear understanding of how to exploit the parameters and what ranges should actually be defined as to have the most precise results. As it was stated in the discussion part, the study on the simplification of the material's characteristics and its limitations can be taken further by using the outputs from this research thesis and implementing different strategies of analysis. However, the overall results of the final optimization process have showed that the daylight control impact of the expanded metal mesh is significant. In order to strengthen this statement further analysis assessments have been made. The daylight factor, annual radiation, average illuminance and daylight glare probability for critical days and annual average glare hours have been calculated to observe if the improvements in customized Spatial Daylight Autonomy were translated to other measurement methods, which gave similar results as expected. The final step for the optimization was made to obtain a pareto curve maximizing the CsDA value as usual but adding the goal of minimizing the annual radiation as the second fitness value for Octopus. It was observed that, even better results for the CsDA and radiation have been found thanks to the two-degree analysis on which more time is dedicated.

These outputs not only represent the improvements of daylight performance, but also the importance of the daylight modelling. It is very important to introduce critical and strategic inputs to the simulations to get best results to be used. Moreover, this process of optimization can be developed by the suggested additions mentioned in the discussion chapter.

As the energy and daylight performance of the buildings is gaining more and more importance every day, the results of this research thesis have given highly satisfactory results to develop new ideas for sustainable architecture with common materials. Expanded metal mesh can be presented as an efficient shading system whose geometrical parameters are proposing many aspects of improvements to the daylight design.

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