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Investigating the influence of perforated façade skins on indoor illuminance level: a case study

Authors:
Jacopo Gaspari, Department of Architecture, University of Bologna, Bologna, ITALY
Kristian Fabbri*, Department of Architecture, University of Bologna, Bologna, ITALY
Lia Marchi, Department of Architecture, University of Bologna, Bologna, ITALY

* corresponding author, kristian.fabbri@unibo.it

Abstract:

Building shading systems are crucial to both avoid indoor overheating during summer and control daylight inflow. This is particularly relevant in exposed glazed façade during summer, where the risk of excessive solar radiation and light entering the building is elevated. It is even more important in shallow body constructions, where excessive illuminance level can cause severe visual discomfort for users. While the effect of shading systems on building thermal comfort has been largely discussed in the literature, few studies and design-support tools are available with the second field. On this premise, the study proposes the use of Dialux software to support the design of sun-shading devices with the two-fold objective of reducing risk of glare along the façade side and avoiding a dark effect on the opposite side. The procedure is based on a multiple design approach that simulates the effect of diverse shading panel configurations on indoor illuminance distribution. Variations in the panel openness factor and geometry are considered. Then the procedure is implemented on a residential case study in Bologna (Italy), which due to its context constraints resulted to have a limited depth and thus a high risk of excessive illuminance. The results demonstrate that Dialux is sensitive to both changes in the openness factor and geometry of the panel. The multiple simulations allowed to meet optimal illuminance level around 300 lux for more than 70% of the case study room surface while containing the area exceeding the optimal level under 1,000 lux to less than 20% and to avoid reaching the minimum threshold of 100 lux through a shading system with Openness Factor ranging between 11 and 15%. The workflow can serve not only as a tool for addressing and verifying the design choices, but as a design support means itself. Due to its structure and easiness to input data and modelling stage, the methodology has a high replicability potential.

Keywords:

Perforated solar screen; illuminance level; shading devices; Dialux; building performance; daylight.

1. Introduction

The ever-increasing effect of Climate Change (CC) on the living environment calls for urgent actions to reduce the building sector's energy demand and carbon emissions [1]. Buildings are indeed among the major contributors to the world energy need and carbon footprint [2], and thus among the most impacting sector on CC. On the one hand, great efforts have been put to find effective and feasible solutions to retrofit the already existing built environment. On the other hand, increasing attention has been paid to develop new design strategies and technical solutions for highly energy efficient new constructions. Within this second category (i.e., new buildings) novel concepts aimed at reducing the sector's energy demand have arisen in the last decades [3,4] such as Nearly Zero Energy Buildings (NZEBs, as defined by the EPBD Directive 2010/31/UE [5]), Positive Energy Buildings/Blocks (PEBs) or Zero-Emission Building (ZME, definition by new EPBD Recast IV [6]). These concepts strongly rely on the integration of renewable energy sources within buildings that already achieve minimum energy needs due to their sustainable design. This is primarily based on the adoption of passive strategies carefully considering the exposure, orientation, geometry, and constructive features of the building to optimize its thermal and energy behaviour exploiting passive solar gain to ensure thermal comfort or natural ventilation to reduce overheating. Passive strategies also include a reflection about the shape and compactness of volumes to reduce thermal dispersion and maximize the benefit coming from the building insulation layers. Given that the building envelope is devoted to separate indoor and outdoor environment, and especially to control air exchange, water, moisture, heat, and light flows [7,8], great emphasis is given to the detailed design of this technological system in highly efficient buildings.
While in northern European countries the primary scope is still to reduce the energy demand for heating, the progress in energy efficiency of new buildings standards had led to no or very little energy consumption for winter heating in the Mediterranean countries. Therefore, in the NZEBs' and PEBs' field, design frontiers are now focused on reducing summer overheating and thus limiting energy demand for cooling systems [9,10], while maximizing winter solar gains. As global mean temperature is expected to rise, this topic will become even more important in the future years deserving further investigation [11]. Indeed, Climate Change is not only affecting building energy demand for summer or winter air-conditioning, but also liveability of indoor and outdoor spaces in warming cities [12].
Summer overheating and daylight levels are mostly related with solar radiation flowing into the building through windows or other glazed surfaces, and many design solutions have been developed to balance the need for solar heat and daylight gains in winter while avoiding overheating in summer. Many of them integrate air gaps, either as thermal insulation layer or thermal extractor [13], ranging from double-skins façades to ventilated photovoltaic systems.

1.1 The role of shading solutions in the building envelope performances

In order to effectively manage variable seasonal conditions, sun shading tools are among the most recurrent strategies implemented in buildings, either as stable or dynamic systems adapting to environmental conditions [14]. Their effectiveness depends on the technical, material, and geometric features of the shading system, which influence the distribution of indoor illuminance and indoor lighting comfort. In turn this also affect the architectural appearance of a building (i.e., envelope texture), which means other factors than heat-light exchange flows performance enters the design process [15].
An excellent example of integration in this direction is offered by the recurrent use of mashrabiya [16] in both traditional and contemporary Arabic architecture representing not only an important and distinctive cultural element but also a relevant multi-function tool. It serves as solar radiation reduction, light and air flow filtration while ensuring adequate privacy level and aesthetic connotation.

Due to its relevance for sustainable design, this research field has a long track record of studies. A consistent body of literature addresses the overheating control through a wide range of possible sun shading systems with fixed or dynamic configurations; manually, automatically controlled or passively actuated; made of simple fabric or innovative nanotechnologies like electrochromic glazes [17–21].
Many authors have investigated the effect of diverse shadings on both indoor thermal and visual comfort assuming integrated assessment protocols such as Chi et al. [22], who developed a workflow to optimize the design of perforated solar façades considering both daylighting and thermal performance. Similarly did Dagher et al. [23], who tested an evaluation procedure to ensure thermal comfort without compromising the daylight factors inside school buildings. Stazi et al. [24] compared many solar shading solutions in terms of thermo-physical comfort, energy consumption, daylight contribution, and environmental impact through LCA. Uribe et al. [25] discussed how different control strategies (actuators and opening mechanisms) of perforated curved louvers may affect the visual comfort and energy consumption of office buildings in diverse climatic zones.
Most studies focus on thermal comfort alone, for example by exploring the potential of perforated sunscreens as part of a double façade system and focusing on air ventilation through the cavity and passive solar gains [26–28].
Few authors focus instead on lighting control alone as a primary goal of shading systems. As lighting is also an expense voice of energy bill, not to mention the effect on indoor user comfort, this should also be considered in the design process and through software and digital tools comparative scenarios. It can be useful in fact either for evaluating glare risk and excessive illuminance in limited depth buildings or the lack of adequate daylight levels in larger buildings.

1.2 Dynamic solutions and climate-adaptive building shell

In order to optimize and limit buildings' energy demand further, special attention has been given both in the literature and design practice to screening components capable of self-adjusting/reacting according to external lighting or solar radiation levels, including Climate-Adaptive Building Shells (CABS). These allow to control both undesirable heat gains and adequate indoor daylight level, which is particularly critical in highly glazed façade such as in high rise office buildings [25].
In this field, Dabaji et al. [29] compare the effects of a perforated solar screen on lighting comfort with three venetian blind types. As a result, they argue that the first is not always effective in contrasting the risk of glare and ensuring adequate illuminance levels. In their critical review about perforated shading systems, Naik et al. [30] detect several gaps related to the impact of dynamic screens on occupant's indoor comfort, suggesting that a more user-centred approach should be implemented. Day et al. [31] suggest that a number of human-driven factors – among which the provision of quality view and visual comfort – should be considered along with solar heat gains when discussing the design of a façade and its shading systems. Despite few studies addressing dynamic daylight assessment tools and metrics related with shading systems, literature reports high level of occupants' dissatisfaction and discomfort, such as glare, overheating, or uneven illuminance levels [32,33].
These discomfort-related issues can particularly affect the renovation of existing buildings or new volumes included in existing urban fabric where the orientation, exposure and geometrical parameters cannot be freely chosen due to the surrounding building constraints. Additionally, they can be even amplified by the reduced depth of those volumes which must keep a minimum distance from other buildings or from the street alignment due to local regulations. In fact, given that building indoor Illuminance level is affected by depth and proportions of indoor spaces too [34], the illuminance issue is highly relevant to those buildings that have limited depth because of dimensional constraints, as it is often the case of infill interventions in densely built urban environments. Typically, the less the depth of the building block, the

higher is the risk of glare and excessive illuminance indoor. As a result, an excess of light can affect occupants' health, wellbeing, and productivity [35].
Literature about shading technologies reports several research projects on software simulations [36] and their impact on building design [37–40] or shading devices in buildings [41–43]. Also, given that shading design patterns have a role to define architecture, some authors address shape morphing to control solar shading [44–47].
Within the body of literature about the application of natural lighting control, some articles study the relationship between indoor daylight and indoor artificial lighting control system [48,49], other report scenarios with and without automated blinds, by calculating daylight illuminance and daylight glare index through windows [50]. In this case the openness factor depends on the reflection angle of daylight. Some study simulates venetian blind as a sun-shading device (i.e., system that allow to control openness factor or flip angle orientation) and evaluate indoor thermal comfort. He et al. [51] and Fedorczak-Cisak, et al. [52] evaluate the relation between outdoor climate data, including solar irradiance, and indoor thermal comfort measured and calculated with PMV and PPD indexes. Other studies describe a control method for automated blind or a blind control algorithm to maximize occupants comfort based on their perception and preferences [47,53,54].
Despite the literature offers several studies focused on shading device design considering the resulting thermal comfort, the deriving impact on indoor illuminance or integrated assessment [55], it emerges that few studies are devoted to providing design indications or procedures to optimise the indoor illuminance level with relation to the geometry and features of shading devices, reversing the research perspective.

2. Goals

The purpose of this study is to investigate the distribution of natural light in the indoor environment when a shading system is adopted to mitigate relevant sun exposure with reference to some conditions which may stress discomfort. It is therefore referred to indoor spatial distribution of daylight and sky luminance following CIE standard, particularly ISO 15469:2004/CIE S 011:2003 [56]. The luminance distribution of the sky depends on weather and climate conditions on daily and seasonal basis as well as on the orientation to the sun. For the scope of this study, summer stressing conditions are adopted with the goal to investigate how to address the response of façade shading system, keeping the illuminance level as key variable, when south oriented glazed surface are highly exposed. This happens when the zenith luminance is maximum with reference to CIE Standard Overcast Sky coordinates in the boreal hemisphere. The exposure condition is defined considering: a) the climate data of hottest day of the available previous year and b) daylight and sky luminance referred to CIE Overcast Sky standard for south orientation at 13:00 of the hottest day.
It must be noted that the study is only addressed to investigate the illuminance level and not the solar radiation.
The general objective is therefore to define a methodology to support the design of sun-shading devices that allow to ensure suitable illuminance indoor level as a response to summer daylight solicitating conditions. The proposed methodology considers the adoption of a shading device based on a screen (typically a flat or corrugated perforated panel) placed in front of the glazed surface and does not consider the use of louvres or the shading effects generated by cantilevered elements which require a completely different design approach.
The illuminance effect of alternative design scenarios of the shading devices is explored throughout software simulation. Among the available commercial software, Dialux [57] is chosen for its user-friendly interface which makes its use at professional level easier and quicker, for being an open-source and free application, and for its accuracy, reliability and effectiveness which have already been proven in several studies [58]. The software essentially simulates the movement and intensity of sunlight throughout the

day, allowing designers and planners to understand how natural light will impact the illuminated area, aiding in the design and evaluation of lighting solutions for indoor and outdoor spaces.
Compared to its early years, the functionality and the quality of algorithms have been improved switching in example from pure radiosity to hybrid ensuring a quite realistic response. The foundational aspects handled by the complex trigonometric and mathematical formulas translated into its algorithms deals with the solar declination, the solar hour angle, time correction, atmospheric refraction taking into account the location via longitude and latitude coordinates.

3. Methodology

The research investigates the effect of the following design variables on indoor daylight distribution: (i) Openness Factor (OF), and (ii) panel geometry.
The evaluation is performed with Dialux, which enables calculation from entire buildings to single rooms, with artificial lighting, daylight, and emergency lighting. It also supports the compliancy check of regional or international standards. Among the initial assumptions there is the need to consider the winter period passive gains and the possible request of the end-user to override the shading system, thus it is thought to be an openable solution that can be considered always open during winter. For this reason, the potential effects during winter are not investigated. Only summertime is assessed as the goal is to possibly avoid any operating condition leading to exceeding acceptable (when not suitable) illumination levels.
The proposed methodology can be graphically represented by the diagram in figure 1 and it includes the following phases:

a) Identification of the *input data* required to perform the evaluation, including geometric and material features of the sample;

b) implementation of a multiple design procedure, simulation of several scenarios with Dialux software [57];

c) generation of a matrix to compare diverse scenarios obtained in different times of the day (i.e., results).

This workflow has been applied to a case study located in Bologna, as described in the following paragraphs.

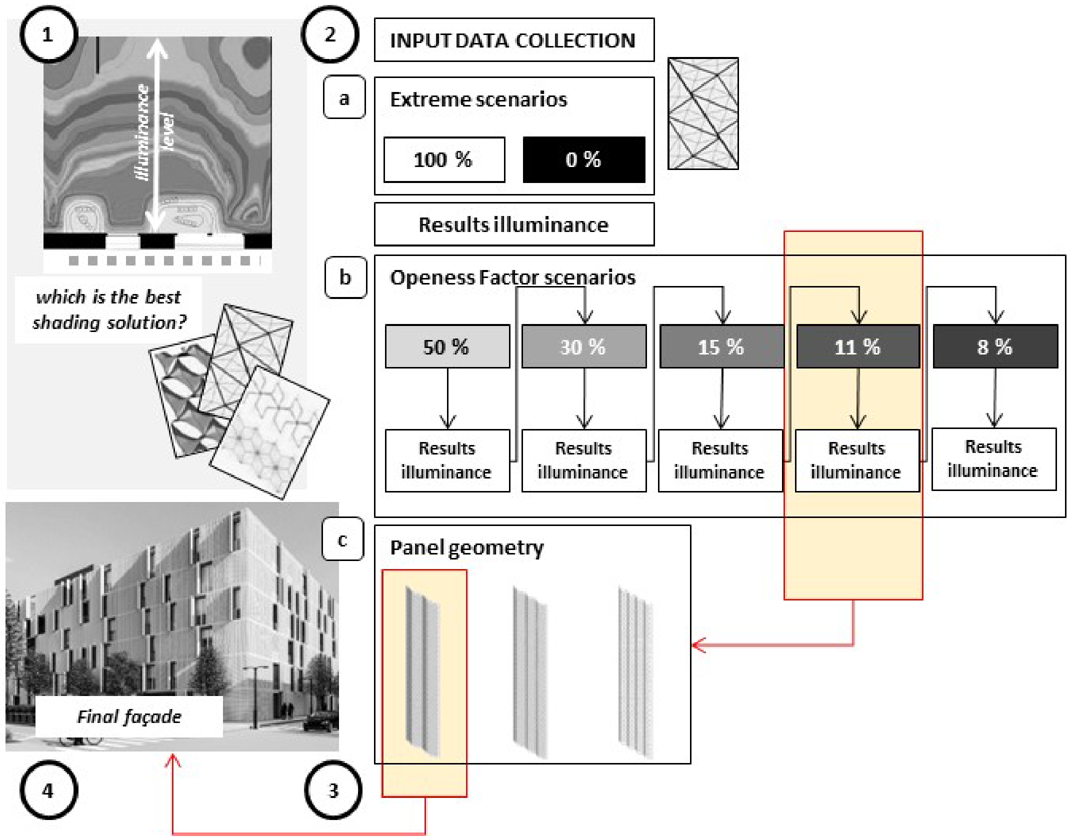

Figure 1. Workflow to select the best shading panel configuration. Elaborated by the authors.

3.1 Input data collection

The first step requires the collection of three categories of data to perform the evaluation through Dialux:

1. Geometric features of the building unit sample (either a representative room of dwelling or office space), including dimensions and configuration, as well as orientation, position, and geometry of the windows. In case of multiple orientations of the building, the most exposed façade must be selected.
2. Shading system geometry and dimensions (e.g. floor to floor panel, modular panels in width and height, etc.).
3. Shading system possible openness factor, material choice and shape (e.g. number of perforations, distance between perforations; type of material: metal sheet or GRC or wood panel; flat or corrugated or waved panel).

3.2 Scenario evaluation and comparison

According to the workflow a multiple design approach was followed:
a) at a first stage, the “extreme scenarios”, without shading and with a fully opaque shading are evaluated, respectively. This way, the highest and lowest illuminance distributions are obtained for calibration purposes and for better setting the alternative scenarios.
b) at a second stage, the effect of diverse *Openness Factor* (OF) percentages, namely 50% OF, 30% OF and 15% OF, in a flat frontal screening panel is simulated assuming the 50% as the intermediate condition and then proceeding with approximately 1/3 incremental steps Being the first results not fully satisfying

in terms of filtering capacity, 11% OF and 8% OF were also simulated to widen the reflection about the potential impacts.
c) at a third stage, after choosing the most appropriate OF value – compliant with the standard and user preferences – diverse panel geometries are evaluated, namely wavy (with three different paces), corrugated and ribbed.
The evaluation starts by modelling the building's sample unit and shading panel in the software; then the illuminance level distribution (lux) is evaluated during August 12th, 2021 (sunrise 06:13 culmination 13:19, sunset 20:24, daylight duration 14h 11m 16s), assumed as the hottest day of the year before. This day is conventionally used for dynamic building energy performance simulations, and it is supposed that – considering the extreme conditions – the shading panel is operating. Therefore, it is important to verify that a minimum average daylight level and distribution is ensured even in this scenario.
After selecting the day, the simulation is run for three hours in the day: mid-morning at 11:00 (solar altitude 48.17°, azimuth 123.98°), mid-day at 13:00 (solar altitude 60.04°, azimuth 170.47°), when sun achieves its path culmination, and mid-afternoon at 15:00 (solar altitude 53.48°, azimuth 223.53°). These hours represent those with maximum solar radiation incidence during the day, because before 11:00 or after 15:00 solar altitude is lower than 48° and so such shading devices are not effective.
Then, as shown in the results paragraph, Dialux scenarios are organized in a more systemic way within a matrix for a comparative review where the time hours and the variables are respectively listed in the rows and columns. This enables the design team to select the most appropriate shading panel or run other tests to refine the process and achieve a more effective filtering capacity.

4 Case study

A case study is adopted to test the methodology assuming the constraints of a real site and particularly the one of an infill project within a regeneration initiative. The building is located in a district north of the railway station in Bologna, a city in the mid-north of Italy. According to the Köppen-Geiger [59,60] classification the area falls under the Humid subtropical climates (Cfa) Mediterranean Climate, humid climate with short dry summer and heavy precipitation occurring during mild winters.
The case study is part of a larger renovation process involving the Bolognina district where, the highest rate of social housing in the city is concentrated due to the historic vocation of working-class neighbourhood of the site. As a consequence, the urban fabric – which was originally organized from the beginning of the last century in regular plots – became even denser in the following decades, during the post war reconstruction period and in more recent time increasing the impermeable surfaces at the expense of the available green spaces. This is also due to a gentrification process which is feeding the rental market and the growth of new building for higher income target due to the proximity to the city centre and the major mobility nodes.

4.1 The building

The new housing is planned as positive building infill to re-shape a corner urban front – highlighted within the red circle in the aerial view (Figure 2 and 3) – and to add new value to the existing block. The dwellings are mostly devoted to temporary rents, being the area close to the train station and several cultural and office workers hubs of the city.
In order to fill the gap and align with the built-up fronts without disrupting existing openings, the new building must have quite limited depth (5.4 meters) with the main façades west and south oriented. These initial constraints expose the building to an increased risk of excessive indoor lighting during summer.
The building is designed based on an 80-centimetre module. Windows are distributed accordingly, to ensure appropriate furnishing layout inside (given the small size of the studios there was no room for

error and incorrect use of space) and maximizing the quality of views on the surroundings. A maximum number of three full-height windows are placed in each dwelling, which could be either three single units or one single and two paired units. A frameless glass balustrade faces each window for safety reasons.

Figure 2. Location of the case study within the Bolognina district (Source: Google Maps).

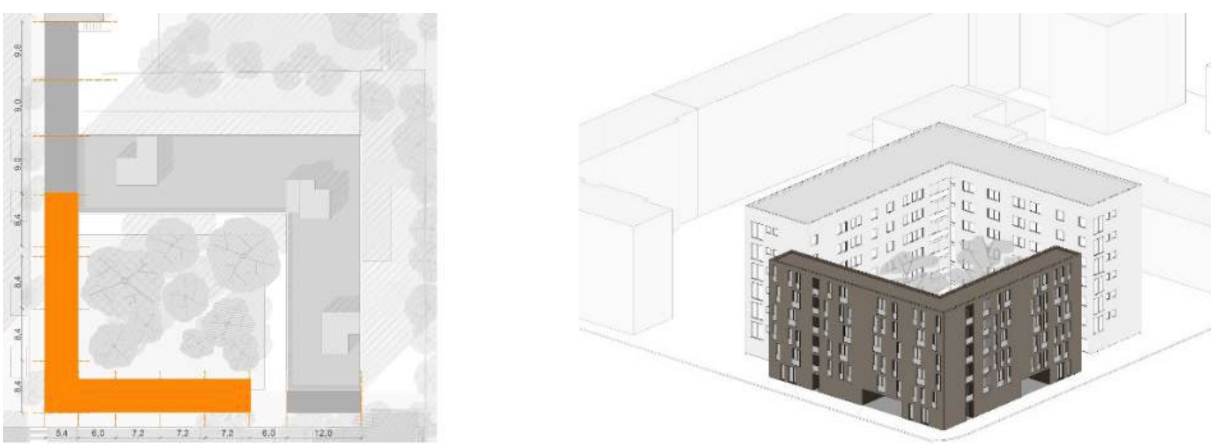

Figure 3. The new building reconfigures the two urban fronts. Elaborated by the L. Patacconi and M. Stefanini.

Assuming street fronts as preferential views (both in terms of orientation and with relation to urban layouts), it was necessary to carefully evaluate the construction choice and its figurative consequences in order to ensure optimal levels of comfort and quality of interior spaces while providing adequate protection for visual introspection. Complete opening (override) of the shading panel is chosen to meet

all these requirements when needed. A shading system made of perforated metal panels (light-finished) was designed, and the effects of diverse panel geometry and openness factor was investigated to ensure visual comfort inside. The panels follow the shape of the openings, which are narrow and high. When placed over the windows, the panels are openable, while in the remaining part of the elevation they are fixed as part of the cladding system. The panels are fixed by means of a metal sub-structure to the façades, which becomes a guide to allow the panels to slide in front of the windows.
The opening mechanism is manually operated so that the end-user can always adjust it according to his/her own preferences. Only in specific case due to physical distance or other user-related obstacles, it can be assumed to be mechanically actuated, but this is expected to have no impact on the evaluation.

4.2 The room and the panel design

The workflow described in the previous section was then implemented to the case study. The sample dwelling was selected among the one more exposed to solar radiation (i.e., in the south façade, at the highest floor level). Basic input data including the size and the window positioning were collected, as well as those regarding the perforated building skin features and its possible variations. As shown in Figure 4 the access door to the 32 m^2 studio is not considered as a source of daylight as it is opaque and shaded by a covered walkaway located on the opposite side of the street elevation.

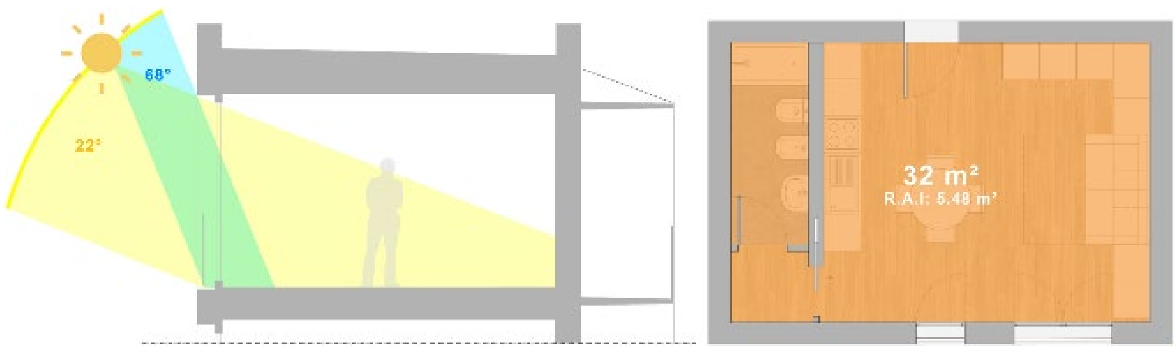

Figure 4. Sample dwelling unit in section and plan. Elaborated by L. Patacconi and M. Stefanini.

As represented in figure 5, the shading system is defined as a panel 0.80 m width and 3.20 m tall which is divided into two elements 0.40 m each to let them fold and slide on one side of the window ensuring an easy override mechanism for the end user. In order to reduce the weight of the cladding and the shading system several construction materials and systems were initially considered to finally limit the options to wood and metal. Despite wood would particularly fit both the sustainable design of the building and its LCA profile, the recurrent maintenance actions required, and the shorter expected service life of the envisaged components finally led to choose a metal-based solution which allowed to keep quite small section of the supporting elements, to work with a quite thin screening layer and to ensure high durability and no or very few maintenance actions. The choice also matched the architectural façade effect wrapping the whole elevation and increasing the chance to explore alternative options to increase or decrease the openness factor of the screening layer.

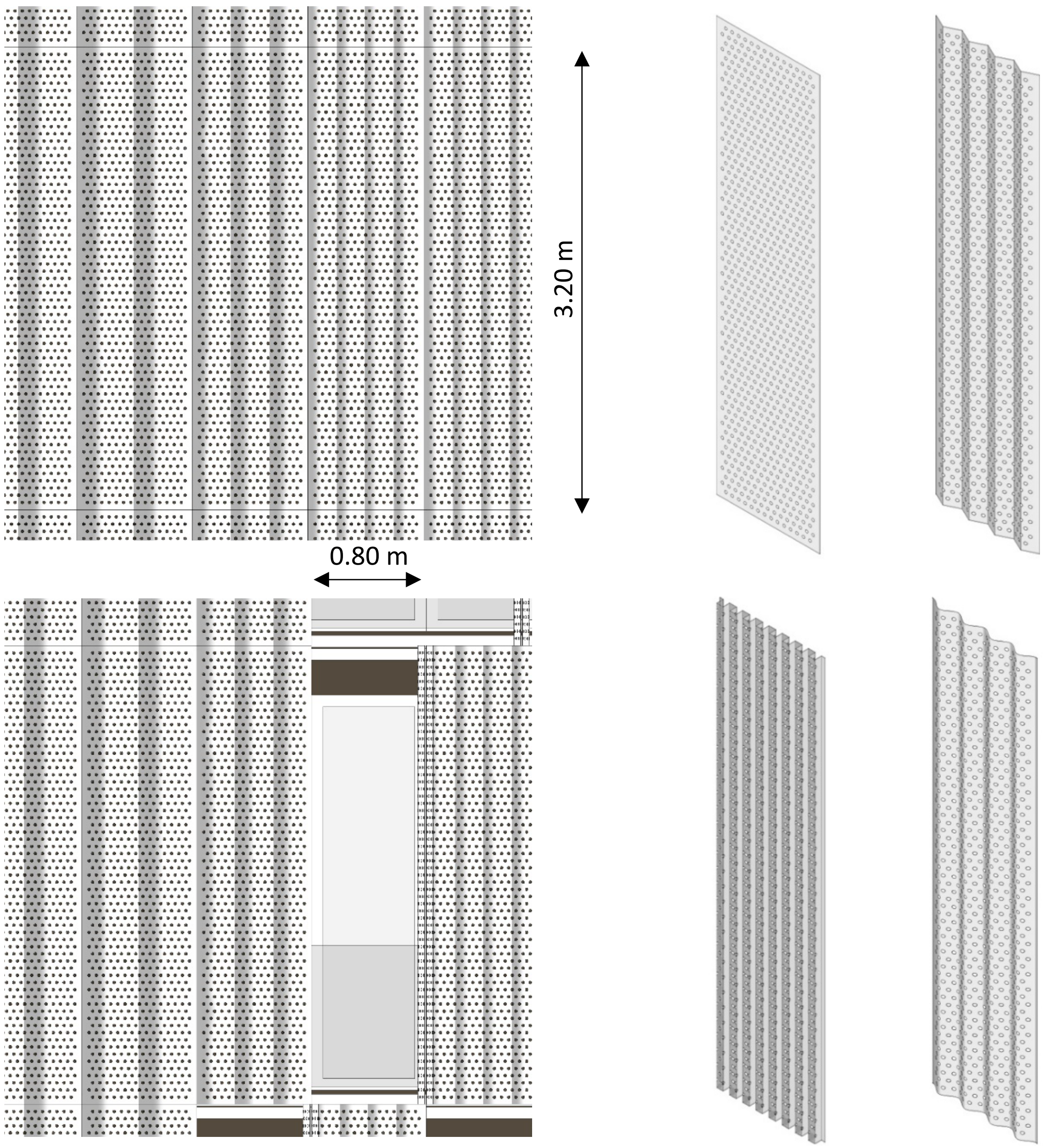

Figure 5. Layout drawings of the shading system and override position (bottom) with alternative panel sections from flat sheet to wavy sheet.

5. Results

As described in the methodology paragraph, a comparative analysis of alternative configurations supported the decision-making process and the following detailed design of the perforated metal skin.

5.1 Extreme scenarios

When no shading panels are in place, meaning a 100% OF scenario, results show (figure 6a) that in all the three considered time slots the indoor lux values exceed the permitted thresholds (ranging between 150 and 1,000 lux for closed spaces). At midday, in the area closed to the windows a value of 50,000 lux is reached, leading to high discomfort levels for users. This solution was not analysed as a viable option but considered as baseline on how daylight impacts on the sample dwelling without any shading system making evident not only the high level of possible discomfort but also the need to adopt a mitigative device. The opposite condition, meaning a 0% OF scenario using a fully opaque shading panel, results show (figure 6b) that the indoor lux values do not reach the minimum threshold of 100 lux at any time slot. This solution was obviously not considered for the purpose of the study but to set the opposite scale range and to let the architectural designers discussing how to darken the dwelling during sleeping time (this was finally managed with inner rolling blinds completely separating this function from the outer skin).

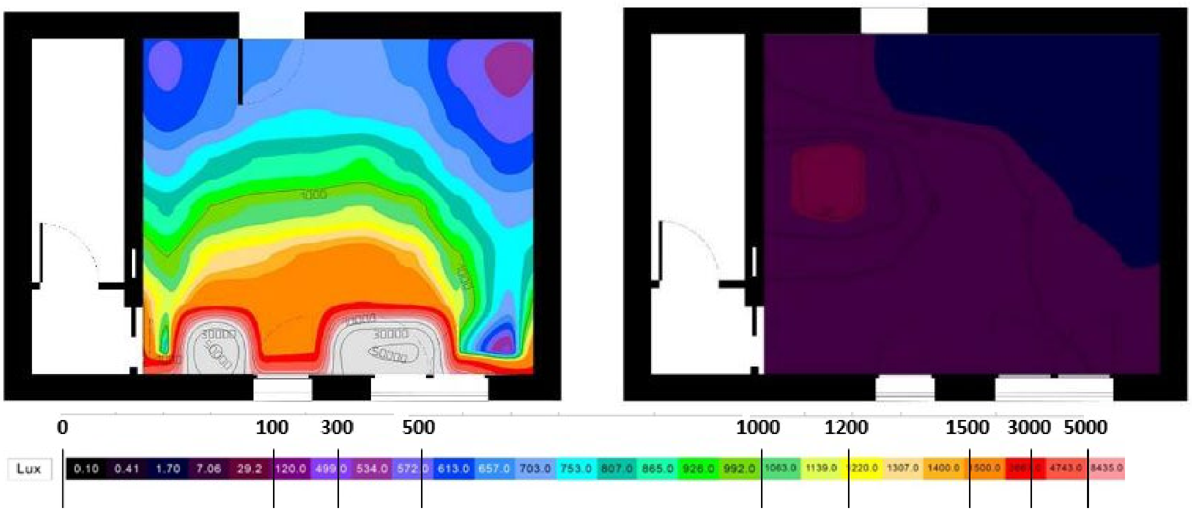

Figure 6a.b. Scenario 100% OF at 13:00 (a): Illuminance distribution with no shading reaches very high level of discomfort. Scenario 0% OF at 13:00 (b): a very dark daylight distribution is obtained with the opaque shading for setting and control purpose only.

5.2 Openness Factor scenarios

It was then decided to use perforated metal sheets for the shading panel and assess which percentage of holes (in commercially available size) would provide the most appropriate illuminance level in the case study. As explained in the method section, the first considered OF scenario was 50%, which basically led to satisfy the average level of light in the room but leaving a significant area of discomfort closed to the window where at 13:00 approximately 20,000 lux was registered as showed in the comparative diagram of figure 7 where OF variations are placed in each row.

Therefore, a progressive decrease of the OF was adopted, testing first a 30% reducing the level near the window to 10,000 lux – which was however still exceeding a comfort threshold – and then a 15% which partially met the expected level but not during the entire considered time slot.

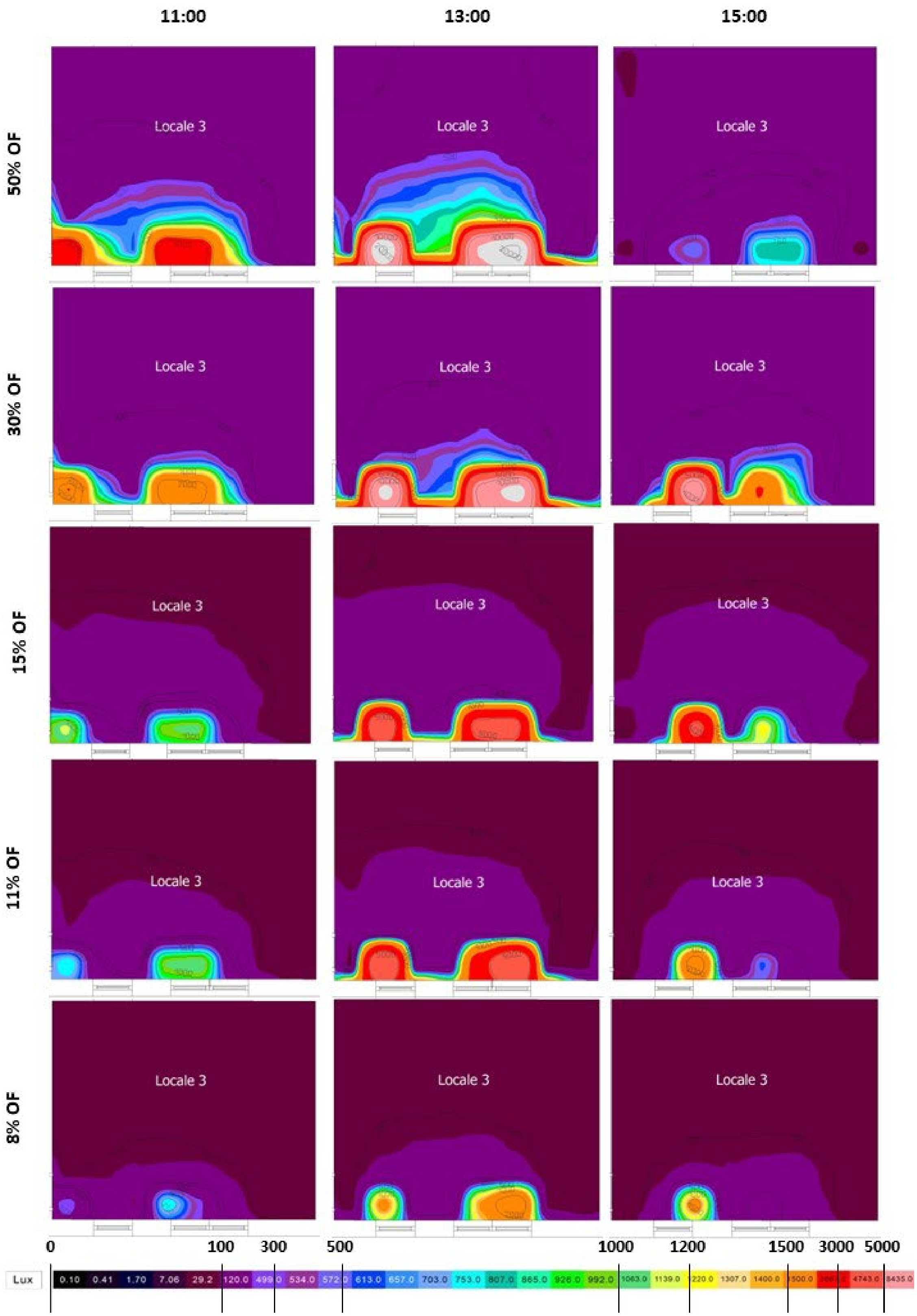

Figure 7. Comparative diagram of the diverse indoor illuminance levels due to changing in Openness Factor (OF) in the perforated metal sheet.

Halving the percentage further and verifying the scenario of 8% OF, the comfort level was not achieved during the full day and despite the lux value could be considered acceptable closed to the window, it was not meeting the minimum threshold of 150 lux in the rest of the room. Thus, an intermediate optimised OF scenario corresponding to 11% was finally tested. This value made it possible to achieve acceptable lux values in the area near the windows at any time of the day, and a sufficient illuminance level in the remaining part of the dwelling as well. Consequently, to provide a more balanced distribution on the opposite side of the window, an additional glazed element was placed above the access door to let light entering from both sides.

5.3 Variations in the panel geometry

The following stage investigated the possibility to shift from a flat panel to a waved one, analysing the eventual impacts on shading capacity. This shift is due to the need to adopt a very thin metal sheet (not exceeding 12/10 mm) and keep the large-size panel as lightweight as possible for facilitating the side-folding override mechanism. However, this solution can suffer possible deformations on its own plan, being the vertical dimension particularly stressed for figurative reasons.
To avoid this risk, two main solutions could be adopted: i) provide the panel with a rigid frame in the back to aid in resistance to cutting, ii) shape the panel itself with vertical ribs obtained directly folding the metal sheet so that it resists for its own shape. The second option was chosen with the purpose to reduce the amount of material and the overall weight while keeping a minimum thickness which was to be considered a key requirement.
Three options, namely a corrugated (fig. 8.a), a ribbed (fig. 8.b), and a wavy (fig. 8.c) profile for each version of the panel were additionally explored through Dialux to evaluate the impacts of the changings in the perforation patter on indoor illuminance levels. Inspired by SANAA's New Bocconi campus in Milan (Italy) [61] the last option was shaped with three different curves to possibly obtain a curtain effect as close as possible to a fabric. The results are showed in the comparative diagram of figure 9.

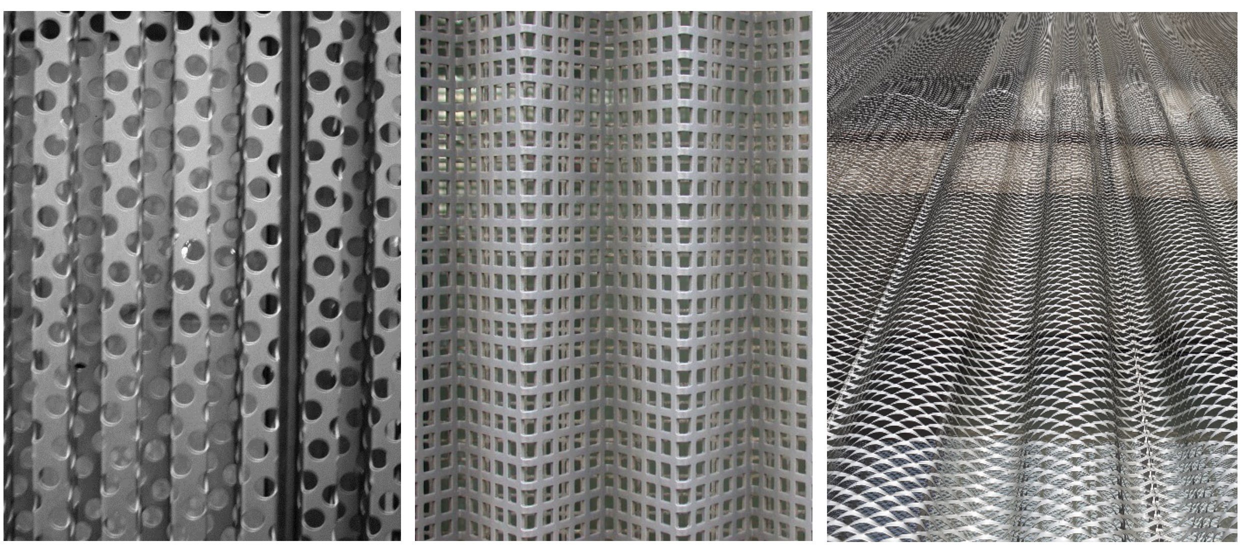

Figure 8a.b.c. Alternative sections (a) corrugated, (b) ribbed, (c) wavy explored for the shading panel. Source: authors' archive.

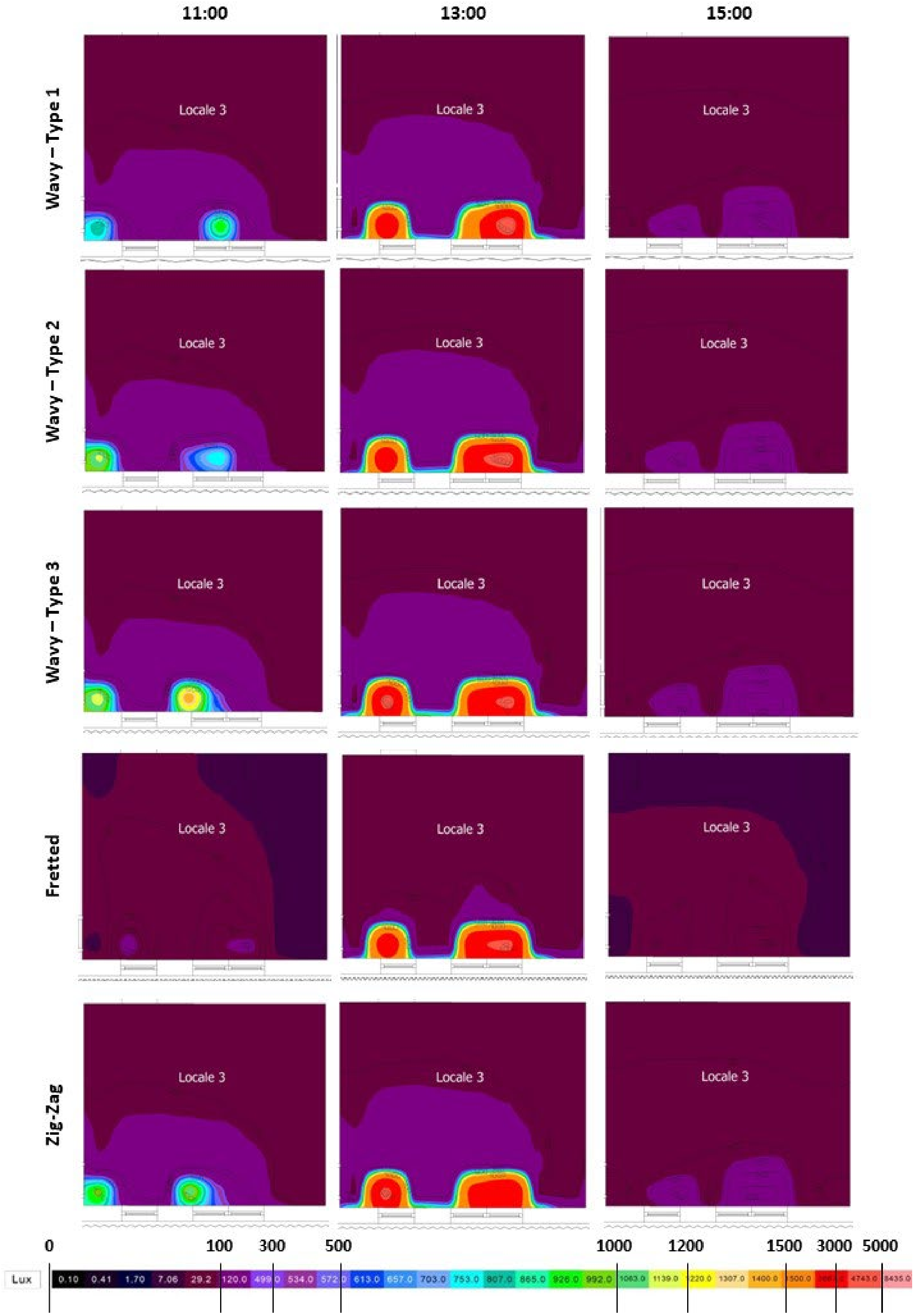

Figure 9. Comparative diagram of the diverse indoor illuminance levels due to changing the wavy or corrugated section of metal sheets whose perforation may influence the defined OF.

6. Discussion

A preliminary outcome of the study is demonstrating that Dialux software – which is not originally designed for this scope – can be effectively used to model and analyse different shading system configurations considering variations with an adequate level of detail in the related results. This relates to both the openness factor and the geometry of the system confirming to be a valid and helpful tool to support the definition of the façade characteristics and layout. It also demonstrated that indoor illuminance distribution can be visibly affected by very small changes in the shading panel.

Adopting a multiple design approach, it is possible to develop a step-by-step methodology to shape the architectural response to be as much effective as possible with relation to illuminance levels. Accordingly, the designers in charge of the façade development can easily visualize the impact of their choices, preferences and decisions concerning the openness factor and the geometry or pattern before proceeding with more detailed advances.

The study is particularly relevant in buildings with shallow depths and large windows, as in the case study, where it is necessary to meet two requirements: a) to reduce the risk of glare close to the windows; and b) to ensure that the minimum daylight level on the opposite side of the room satisfies ~~is more than~~ the minimum of 100 lux, towards an average of 300 lux, as required by Italian codes and regulations [62,63].

It has to be remarked that achieving a balanced result is not simply meeting a certain lux value in a specific point of the case study room, but to possibly reach the most suitable distribution of illuminance level on its surface. Varying the shading system OF not only the level but also the distribution of illuminance in the space changes. Thus, the following visual comfort thresholds, based on the current national regulations (but this can be easily adapted in different context in case of replication elsewhere), were adopted to analyse the daylight inflow:

- < 100 lux (baseline) - low visual comfort: the minimum illuminance threshold is not achieved and according to regulation the space is too dark for specific activities (such as reading or working for which artificial light is consequently needed) but is acceptable for other domestic activities.
- 100 lux ÷ 300 lux (average) – average visual comfort: illuminance level meets the minimum suggested requirements by the national regulation.
- 300 lux ÷ 1000 lux (optimal) – optimal visual comfort: illuminance level ensures suitable conditions to perform any kind of activities with optimal comfort levels.
- > 1000 lux (discomfort limit): it has to be noted that the current regulatory framework does not fix a limit, however exceeding 1000 lux glaring, and other discomfort phenomena start to increasingly affect the occupant conditions. Accordingly, this value is assumed as discomfort threshold limit.

Figure 10 shows an elaboration of figure 7 diagrams where the isolines corresponding to 100, 300 and 1000 lux thresholds are included to highlight both the depth and the percentage of the room surface falling into the prevalent illuminance condition (and representing the corresponding main comfort/discomfort situation). Each row is referred to the OF investigated variation and each column is instead referred to three significant day time slots (namely 11:00; 13:00; 15:00). It can be easily noted that with a 50% and 30% OF, the shading system allows the illuminance level overcomes the 1,000 lux threshold in the windows area for a depth between 1 and 1.5 meters which progressively decrease to 300 lux in a depth that ranges between 1.7 and 3.4 meters apart from 50% OF at 13:00 which always exceeds 300 lux (95% of the surface). This could sound as positive results considering that, depending on the daytime, between 39% and 62% of the room reaches optimal illuminance levels. However, both 50% and 30% OF produces a band of potential visual discomfort or glaring area along the windows which weighs between 10 and 15 % of the room surface.

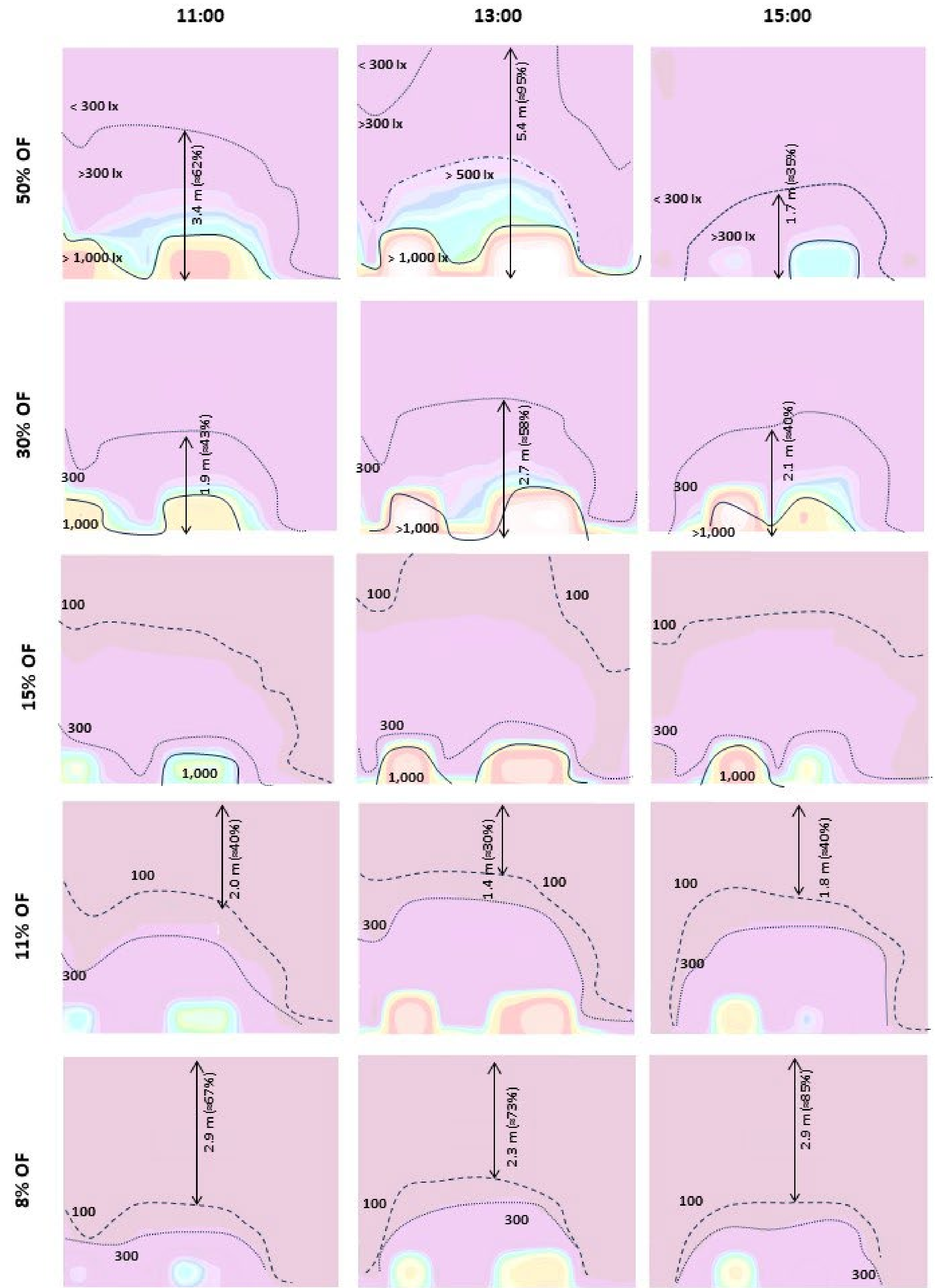

Figure 10. Comparative diagram of the diverse indoor illuminance levels considering the minimum, the optimal and the limit thresholds to meet visual comfort according to the OF variations.

Despite a small area reaches or slightly exceeds the 1,000 lux threshold the 15% OF scenario seems to be the most balanced one largely meeting the optimal 300 lux illuminance level in more than 70% of the room area during the day. Progressively decreasing the OF percentage to 11 the critical area closed to the windows is attenuated under the 1,000 lux limit however the illuminance level on the opposite side of the room falls under the minimum threshold of 100 lux with a depth that ranges between 1.4 and 2 meters which corresponds to 30÷40% of the room surface which can be reasonably considered the limit of acceptability. Then the room becomes too dark, as 8% OF demonstrates.

Therefore, depending on a combination of requirements and preferences an OF between 11% and 15% ensures an optimal and balanced illuminance level in the room for more than the 70 % of its surface and keeping the rest within acceptable visual comfort conditions.

The results confirmed that perforated building skins are not always as effective as supposed in reducing risk of glare or ensuring adequate illuminance distribution, as pointed out by Dabaj et al. [29].

The analysis of the effects of any variations in the geometry of the shading panel section demonstrated that not only they have an impact on the illuminance level, but that Dialux is sensible to due changes in daylight distribution. Although wavy or corrugated effect is recurrently adopted by designers to obtain a more vibrant and appealing façade, this can sometimes negatively affect the functional shading effect or at least alter the expected related illuminance level. In the examined samples, 'Wavy Type 1' and 'Corrugated Type' do not meet the required thresholds becoming less interesting in terms of performance response. That said, it must be remarked that façade design cannot be simply reduced to the outcome of numerical procedures and definitely the response to the mentioned requirements (i.e., solar radiation shielding and visual comfort) must be obtained meeting the designer's conceptual image of the façade and of the building overall. In the proposed case study, the initial idea driving the design concept was to possibly wrap the whole street elevation with a homogeneous curtain-like element working at the same time as building skin and daylight shading system. Thus, the study offers a supporting tool to address the design choices staring from the initial concept and providing step-by-step evidence of the deriving effects and impacts of possible alternatives until an optimized balance is obtained.

Considering that no test chambers or other real models were used for validation due to resource and time constraints, a quality assurance process is conducted for the use of Dialux software recurring to a comparative approach with the available literature. As already verified by Mangkuto [64] and Moraes [65], the software is validated against the Analytical Test Cases of CIE 171:2006, coherently with the information released by the software house[66] . The compliancy with the corresponding standards [67–69]was already confirmed by Maamari et al.[70], demonstrating the reliability and a well-established use of the software in the literature. Despite the accuracy of the simulation is not at the core of study, a validation session to assess the results for both OF and panel geometry is not excluded to be performed in a following stage using models or mock-up case studies.

7. Conclusions

The article focuses on the capacity of perforated building skins not only to avoid overheating, as recurrently studied in the literature [71–73], but also to ensure adequate daylight distribution and visual comfort indoor level [74]. Whether it comes of an office or housing space – as in the presented case study, the issue is particularly relevant for exposed glazed façades in energy efficient buildings during summer. In these building typologies, in fact, minimum energy expenses for all operations, including lighting, are considered a must. At the same time, the user comfort and wellbeing are sought, and their combined interrelated impacts and effects are considered design frontiers in this field which can benefit from such a study.

The proposed multiple design approach yields outcomes that can usefully address the building's shading system shaping process. The simulations allowed to critically evaluate the design options which in the case of shading system with a 30 to 50% OF lead to unsuitable glaring or discomfort situations in approximately 15% of the room surface although an optimal illuminance level is reached in the rest. Accordingly, the solution was progressively refined to avoid the inconvenient condition and to meet a balance where more than 70% of the room surface meets optimal condition with a residual part that reaches acceptable illuminance levels over the 100 lux minimum threshold limit.
Dialux modelling software was profitably used for supporting the refinement and calibration process of the Openness Factor of the shading system, demonstrating the effectiveness of the method in guiding the decision-making process. The methodology is highly replicable, adjusting the specific goals and the possible design alternatives to be compared as already emerging from the literature in this specific field [75–77]. On this basis, possible future developments of the research can involve the construction of mock-up or real case studies measurement to assess the accuracy of the presented values, or the simulation of other shading systems or contexts and even how the level changes dynamically along the daytime in the case an adaptive solution (CABS) is preferred. Some studies, such as Yeadon (2014) [78,79], Preto (2019) [80], Globa et al. (2022) [81], Naik et al. (2022)[82], already investigated the chance to drive the dynamism automatically controlling the amount of light and heat together. This confirms the growing interest and attention towards this branch of research and the need for further efforts for further developing our study to include a systematic sensitivity analysis by introducing different daylighting scenarios which could certainly contribute to expanding knowledge and application opportunities.

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