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Use of 3D tessellation in curtain wall facades to improve visual comfort and energy production in buildings

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Abstract. In the vast majority of new buildings, energy and comfort requirements are met mostly by active systems that are often expensive, energy intensive, and complex to maintain. At the same time, advances in the use of digital tools for the design and fabrication of unitised curtain wall systems have substantially reduced the costs associated to non-planar surfaces in building envelopes. As a result, buildings deploy an increasing level of surface geometry articulation that is mostly used for decorative effects. By and large, the flourishing of a new formal vocabulary, enabled by digital tools, rarely translated into buildings that perform better. The research proposes the use of non-planar surface geometries for precise calibration in tilt angle and orientation of individual panels in curtain walls, as an effective passive design strategy. The goal is to improve visual comfort for users, limiting potential glare without the use of shading or blinds and, at the same time, to provide high potential for PV production without negatively affecting daylighting levels in the building interiors. The study explores four families of three-dimensional geometries, based on size limitations and other design constraints typically associated to unitized curtain wall systems. The investigation takes into account aspects such as local climate data, orientation, glass properties, morphology of the façade unit, indoor visual comfort, energy efficiency and energy production. Results show that all four families can be optimised to meet LEED requirements of sDA > 50% and ASE < 10% in office buildings, delivering better performances when compared to a flat facade.

1. Introduction

1.1. Visual comfort

Daylight is recognised to be a significant factor contributing to indoor environmental quality. Several methods integrate daylighting and thermal analyses to reduce energy consumption in buildings, linking a range of occupant's environmental preferences, optimisation of energy costs and office workers' productivity [1]. Researches and reviews have been exploring the effects of daylight on users' behaviour as a way to achieve higher levels of environmental quality inside buildings [2]. Consequently, indoor visual performance has been linked to the physiological comfort of users [3] and defined through parameters such as illuminance and luminance levels, exposure to natural light, and others [4]. In workplaces, daylight and view have been found to be beneficial in creating a comfortable and productive working environment, albeit an excessive exposure towards the outdoor often leads to glare problems, especially for south facing facades [5].



A number of studies focused on factors that acts as triggers to motivate the operation on shading devices in office buildings have been produced in the last years, leading to the categorisation of the impact of daylight based on users' preferences [6][7]. Results showed how a majority of occupants preferred a manual control over an automatic one [8], even though this leads the user's acceptance to be strongly connected with the actuation of the system itself. According to recent research [9], taking into account controlled strategies provided by automatized mechanisms can improve building performance and occupants' visual comfort, but their level of complexity can highly affect the efficiency of the system and therefore the overall performance. Although movable systems tend to achieve a balance between daylighting levels and energy efficiency [10], fixed shading devices and three-dimensional facades for office buildings passively shading from the sun in peculiar periods have been found to be more reliable in the long term because of the reduction of complexity, cost and operational energy [11].

1.2. Solar potential

On-site energy production is considered an important component in many environmentally conscious projects. According to European legislation on Nearly Zero Energy Buildings, for instance, a significant portion of the building's very low amount of energy needed should be covered by its on-site energy production using renewable sources [12]. While higher density in cities carries potential benefits in terms of reduced energy consumption, it also presents unique challenges to the use of solar collectors. As roof surface represents a smaller portion of the total envelope area in taller buildings, facades offer new opportunities for integration of solar panels. Vertical integration is characterised by a reduction in efficiency rate of up to 40% due to their relative inclination to prevailing sun angle. Also, vertical panels compete for sunlight with humans by absorbing a portion of solar radiation and can result in reduced levels of daylight reaching the building's interiors. Until recently, the strategic positioning of solar panels and openings for light and ventilation played out within the limited surface area of flat building facades. Transparent photovoltaics have been used to mitigate the impact of solid panels on daylighting, bringing additional challenges of their own, such as high costs associated to glass laminated PV cells or lower efficiency in thin film technology. Recent studies explore ways to increase energy output of solar collectors while also reducing their impact on interior daylighting by placing panels on movable or adjustable components, such as louvers and light-shelves. While these solutions may result in higher energy production, they can be visually intrusive and often require additional control systems that are expensive and hard to maintain [13]. Such discrete components are attached to structural elements and often protrudes from the building enclosure. They are particularly exposed to high winds, difficult or expensive to transport and install, and prone to damages that are hard to fix because accessible only from the outside of the building. In tall buildings, they can also disrupt window washing systems that use tracks hidden in the curtain wall to operate.

1.3. Non-planar building envelopes

Over the past two decades, additional costs associated to the use of non-planar surface geometry in building envelopes have been substantially reduced. Design-to-production processes involving parametric design software integrated to digitally-driven fabrication technology opened up a new market for highly expressive tessellated facades. Products such as Schüco Parametric System are based on a tubular framing that allows to vary the off-plane angle between contiguous glass panes without incurring in substantial cost increase or technical limitations [14]. The system is clearly geared toward unrestrained formal expression — “unparalleled design freedom” is the enticing promise in a product catalogue by the same manufacturer [15]. Yet implicit in the geometric manipulation of facades is a far more ground-breaking proposition: the ability to optimise each panel tilt angle and orientation based on performance parameters such as incident radiation for energy production and shading potential. Existing research investigates the impact of folding geometries on the energy generation potential of building integrated photovoltaic (BIPV) [16]. Geometric manipulation of building facades can increase the potential electricity generation of BIPV by up to 80%, without compromising the thermal performance of the building, in terms of heating and cooling loads. Additionally, folded geometries widen the spread of useful electricity generations throughout the day, potentially shifting peak electricity to times of

higher demand. Also, previous research has shown that folded facades can secure a number of annual useful daylight hours comparable to flat facades, under certain conditions, provided that an automated shading control system is triggered by excessive indoor air temperature [17]. In a recent study, preliminary analyses suggest that a parametric folded facade can improve visual comfort without the use of additional shading devices, with the folding geometry tailored to perform as daylight control and glare mitigation mechanism [18].

1.4. Aim of the research

A growing interest in passive design principles recognises the paradox in contemporary buildings of relying on energy-driven solutions to achieve energy savings. There are important, unexplored opportunities for providing comfort in buildings within the range of more traditional, low-energy design solutions at the designer's disposal. These solutions can be visually intrusive and might limit formal expression, as compared to active strategies involving mechanical systems hidden away in attic spaces and machine rooms. If considered in the early stages of design, however, they can contribute to an emerging architectural language—one that reconnects *form* to *performance*, where formal features visually inform the users on the flows of energy and materials taking place in the building. The present research explores the potential for passive solar design principles to achieve comparable results in terms of energy performance and visual comfort in buildings, with a system based on optimised shape rather than adjustable components. In particular, the study sets out to advance prior art by demonstrating that a generic curtain wall can meet or even exceed, under certain conditions, LEED target values in terms of daylight and glare risk by virtue of folding geometry alone, without the use of additional devices for shading or glare control. At the same time, careful calibration of tilt and orientation of panels can increase energy production of solar collectors integrated into the facade.

2. Methodology

The study investigates only folding configurations that are deemed economically viable in terms of fabrication, installation and maintenance, based on international construction standards and practice. Although the threshold of acceptability is somewhat subjective, and obviously depending on construction budget, geometries have been selected based on number of facets per unit as main cost factor. Technical considerations regarding construction and installation of unitised modules have not been addressed; however, dimensional considerations have been taken into account.

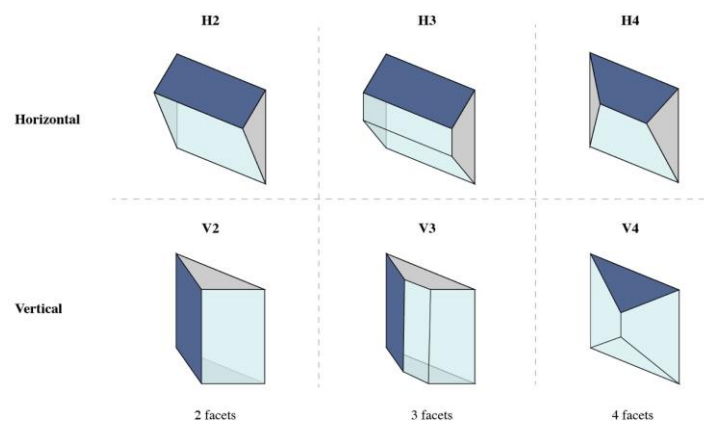


Figure 1. Classification of folding geometries.

From an initial pool of folding geometries with 2, 3 and 4 facets (figure 1), configurations H3 and V4 were excluded because of an inefficient triangular PV panel and/or lower glass panel with excessive tilt angle, making the unit hard to access and maintain from the inside. Selected geometries, in order of increasing complexity, include: a triangular prisms with 2 panels and a single ridge fold, arranged either vertically (H2) or horizontally (V2) over the full height or width of the module; a trapezoidal prism with

3 panels and 2 vertical ridge folds (V3); and a triangular prism with 4 panels and 5 ridge folds, short sides slanted (H4).

2.1. Definition of the standard office module and its boundary conditions

As part of an office building located in Milan (N 45°37', E 8°43'), the description of the office room selected to perform all calculations is adopted from the technical report published by IEA SHC Task 27 [19]. The double office room has just one side exposed, while the other surfaces are considered adiabatic due to the presence of other similar units replicated as part of a modular high-rise building. The light transmittance of the insulating glass unit (transparent part of the facade module) is 80%.

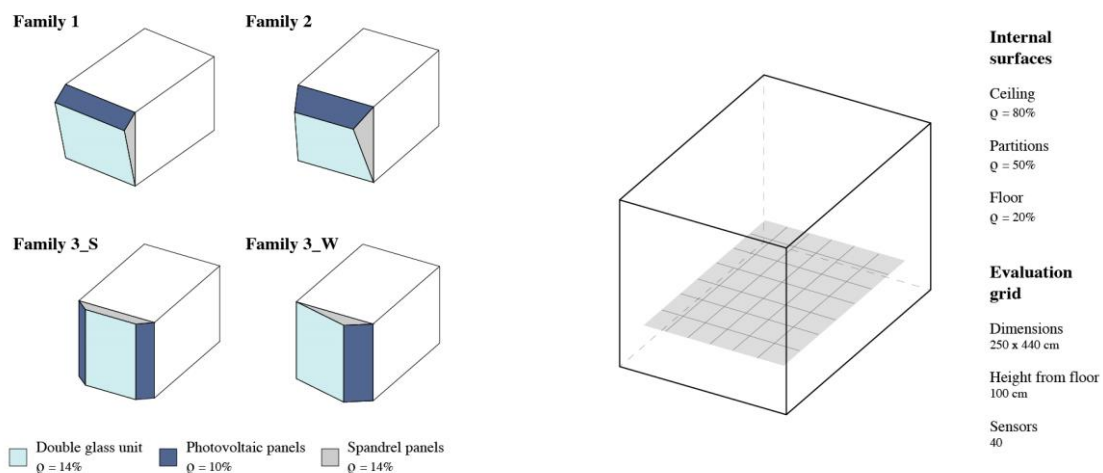


Figure 2. Treatments of each face for the four families studied.

Figure 3. Reflectance of the internal surfaces and dimension of the simulation grid.

Figure 2 shows, for each of the four geometries selected for the study, the materials employed on the different facets – either glass, an opaque spandrel panel, or an opaque panel equipped with photovoltaic cells. All daylight calculations are performed on a 260 x 440 cm grid placed at 100 cm height from the internal floor and equipped with 40 equally distributed sensors (figure 3). The reflectance of the opaque walls (R) is assumed to be 0.5 for the internal walls, 0.8 for the ceiling and 0.2 for the internal floor. Externally, reflectance is set to 0.14 for the spandrel panels, 0.10 for the photovoltaic cells and 0.14 for the double glass unit. No reflectance is set for the external ground.

2.2. Simulation strategy: daylight metrics and schedule

The research explores the effects of four families of folded surfaces applied onto a building facade. Entirely modelled in Grasshopper®, the office room is surrounded by six surfaces, each representing one side or wall of the built space. DIVA is the tool selected to perform annual hourly calculations by taking advantage of the Radiance engine, which allows users to specify the scene geometry, materials, time and date and sky conditions. For the purposes of this work, DIVA is used to run simulations throughout the whole year, evaluating climate-based metrics that fit into the LEED Daylight Credit (LEED v4). According to recent studies [20], the research considers the option 1 provided by LEED v4, which features new simulations based on two main metrics, the Spatial Daylight Autonomy (sDA) and the Annual Sunlight Exposure (ASE). The Spatial Daylight Autonomy should stay above 300 lux for at least 50% of the occupiable hours during the year, while the Annual Solar Exposure should remain lower than 10% to limit the potential for visual discomfort (mainly due to glare). For the purpose of this paper, solutions delivering ASE values above 10%, but still below 20%, will be considered acceptable, since it is expected that the 10% threshold can be achieved with minor adjustments to their geometry and / or the use of adjustable internal curtains. Additionally, Incident Solar Radiation (IR) values, in kWh/year, are evaluated to assess the energy generation potential of PV panels integrated into selected faces.

Each family of geometries is analysed by the variation of tilt angle and length of folds, in search for suitable combinations of sDA, ASE and IR. Each configuration is tested for both the South and West orientations; the East orientation is not considered because of the sun path's symmetry. The simulation process took into consideration an office building schedule, which includes only working days, from Monday to Friday, with an occupancy of 8 hours, from 8:00 to 18:00, and a lunch break from 13:00 to 14:00. The schedule is set following the Daylight-Saving Time (DST) in the DIVA tool.

3. Calculations and discussion

3.1. Family 0 – baseline case with flat geometry

A simple, flat geometry was first investigated to assess its performance without any additional shading device. Starting from a fully glazed module, gradually taller opaque panels were introduced in the upper portion of the module, with the aim of reducing the amount of daylight and direct solar radiation entering the space (figure 4). The tests were conducted in 30 cm increments, ranging from 0 cm (fully glazed module, case 0.1) to 240 cm (mostly opaque module, case 0.9).

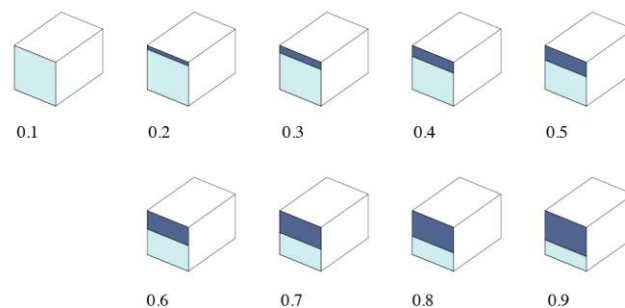


Figure 4. Flat modules with increasing size of the opaque panel in the upper part.

Predictably, in the case of a flat façade without any shading device, sDA and ASE values remain uncomfortably high in most cases, both for the South and the West orientations (figures 5a and 5b). ASE values approach the acceptable 10% threshold only if the opaque panel takes half of the module area or more (case 0.7 and upwards), at the cost of quickly decreasing amounts of natural light entering the space.

Since the opaque panel remains flat (vertical) in all cases, incident solar radiation (IR in figures 5a and 5b) increases linearly with its size.

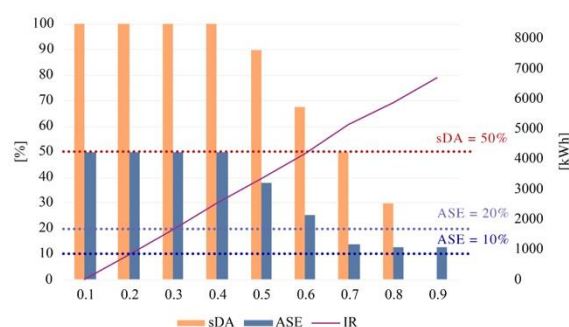


Figure 5a. ASE and sDA for South orientation.

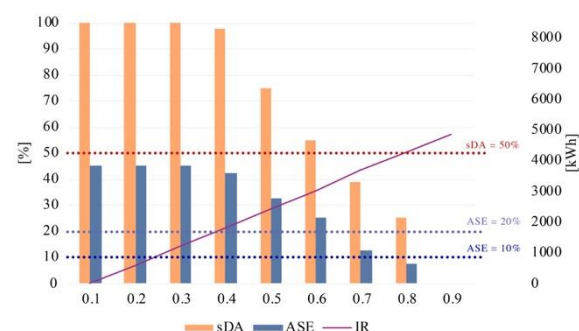


Figure 5b. ASE and sDA for West orientation.

3.2. Family 1 – one horizontal fold

The first set of tests was conducted on modules with a simple geometry, generated by a single horizontal fold. The façade unit is divided in two panels, with the bottom one transparent and the top one opaque (figure 6). The most acceptable configuration from the baseline testing is taken as starting point, with

the module split in two equal parts, each 180 cm high (case 0.7 above, renamed 1.A.1 in the new series). The opaque upper panel, in this case, delivers acceptable values for both sDA and ASE (50% and 14% respectively for the South orientation, since no configuration for the baseline module delivers ASE under 10%). The aim is to verify if a geometric articulation of the façade in the direction perpendicular to the vertical plane can deliver improved sDA values, while keeping ASE within the acceptable range. Shape variations are defined in one series by rotating the top opaque panel, which maintains the same length (cases 1.A), and in the other by elongating the same panel along a plane with constant inclination (cases 1.B).

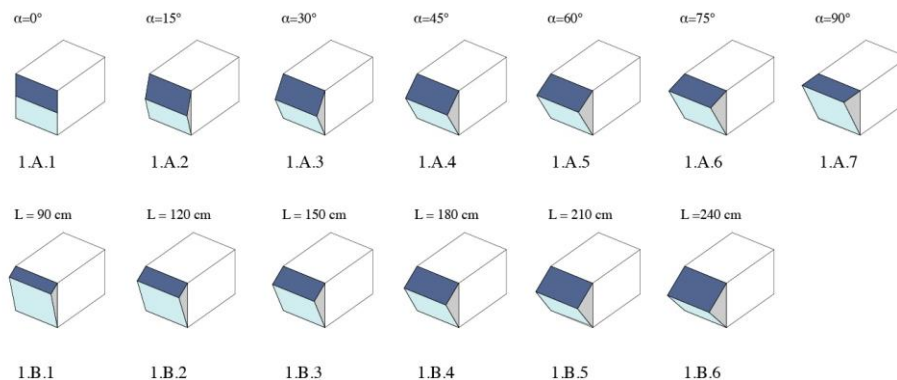
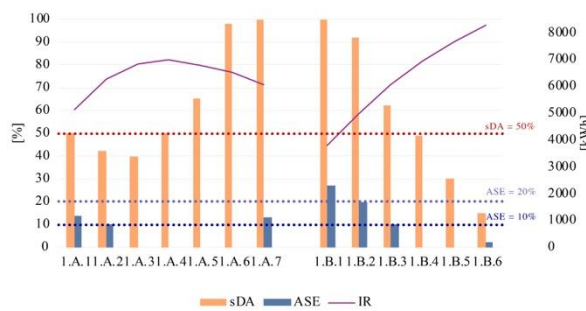
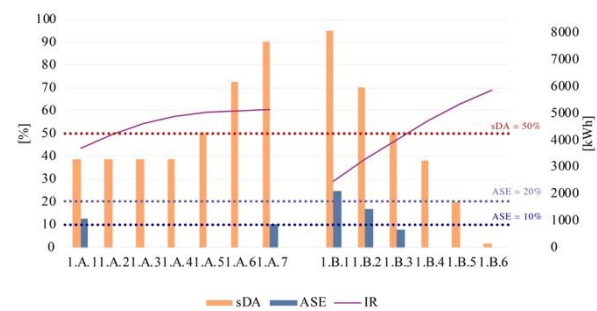


Figure 6. Geometries with constant length (1.A, top) and constant angle (1.B, bottom).

In the case of South-facing modules (figure 7a), the sequence of series 1.A shows increasing sDA values when the angle is larger than 30°, with ASE = 0 until the angle reaches 75°. Solution 1.A.6 performs best, but it should be noted that it protrudes 1.7 m from the reference plane (i.e. the structural slab of the building) and it could prove impractical or too expensive in reality. The sequence of series 1.B shows a more predictable trend to lower sDA values as the opaque to transparent ratio increases. Solution 1.B.2 appears to be a reasonable compromise, with good sDA values and acceptable ASE, that can be potentially reduced with further geometric manipulation (see next paragraph). Solution 1.B.2 is preferred to 1.B.3 because of its remarkably higher sDA value.

In the case of West-facing modules (figure 7b), ASE and sDA values follow similar patterns in both series 1.A and 1.B, but with a slower increase as glass panels get larger. Solutions 1.A.6 and 1.B.2 again provide the best performances, with solution 1.A.7 still acceptable. The same considerations of the South-facing modules apply. Predictably, incident solar radiation is markedly smaller for this orientation.

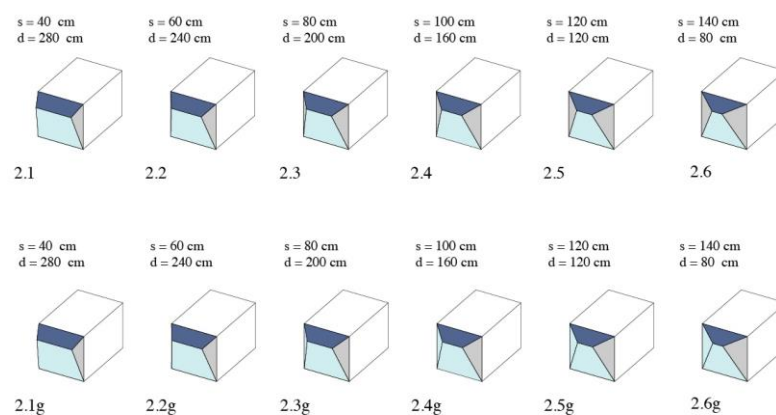
The diagrams also show the amount of incident solar radiation reaching the top panel over a year. Cases 1.A.1 to 1.A.7 show a dependency on the tilt of the opaque panel, with solution 1.A.6 among the ones with higher potential for energy production; although 1.A.4 is the solution with the highest IR value, 1.A.6 appears a better compromise considering visual comfort parameters. For solutions 1.B.1 to 1.B.6, IR values only depend on the size of the opaque panel. In the latter case, solution 1.B.2 is not particularly desirable for energy production, since the amount of opaque surface available for PV panels is limited. Visual comfort and energy production potential, in this case, are not converging towards a single desirable solution.

**Figure 7a.** ASE and sDA for South orientation.**Figure 7b.** ASE and sDA for West orientation.

3.3. Family 2 – slanting sides

The second set of tests is based on the improvement of the best solutions emerging from Family 1 in terms of visual comfort, that is, cases 1.A.6 and 1.B.2, with the latter preferred to 1.B.3 because it has higher sDA values. In fact, only the evolution of case 1.B.2 is investigated, since case 1.A.6 already performs quite well (sDA = 98%, ASE = 0%) and does not need further improvement. Any geometric manipulation reducing the glazed area would simply lead to solutions with poorer illumination.

The further evolution of case 1.B.2 is based on the movement of the two lateral control points along the horizontal transom of the module, in 40 cm increments. It is thus possible to obtain slanting lateral panels which articulate the façade in three-dimensional units rather than a single, extruded shape (figure 8). The intent is to achieve lower ASE values – i.e., reducing glare and direct solar radiation – without affecting too much SDA values. The expected effect of the slanting side panels, which are considered opaque, is to obstruct part of the radiation previously admitted into the room, in particular during the morning and the afternoon.

**Figure 8.** Geometries based on solution 1.B.2 (2.1 to 2.6, top) and solutions with glazed North-facing side (2.1g to 2.6g, bottom).

In the case of South-facing modules (figure 9a), although the introduction of the opaque side panels does reduce SDA values, these remain always above the 50% threshold. On the contrary, ASE values decrease more sharply; although ASE is below the 10% threshold only in one case, the others fall still improve the visual comfort situation compared to the original solution (ASE < 20%, with sDA > 50% as before).

In the case of West-facing modules (figure 9b), if both lateral panels are opaque ASE and sDA values follow similar patterns (cases 2.1 to 2.6), with a sharper decrease and more solutions that result poorly illuminated. However, replacing the North-facing opaque side panel with a transparent one (cases 2.1.g – 2.6.g) delivers definitely better results, with most of the solutions within the optimal thresholds and the rest still in the acceptable range.

It should be noted that, in all cases, the amount of incident solar radiation on the top opaque panel decreases as the side panels converge towards the centre of the module. A trade-off between visual comfort performances and energy production will be required on the designer's side.

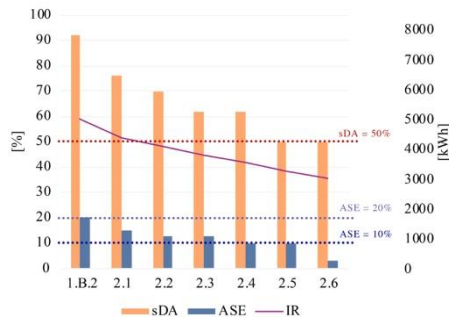


Figure 9a. ASE and sDA for South orientation.

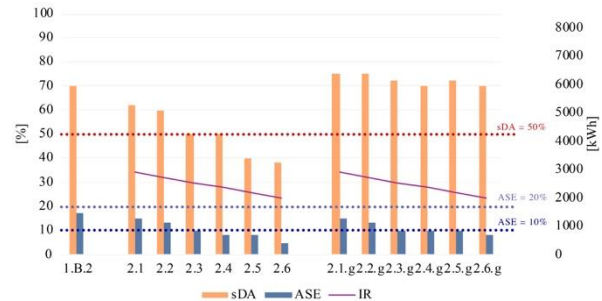


Figure 9b. ASE and sDA for West orientation.

3.4. Family 3_S – two vertical folds

The third set of tests investigates the behaviour of solutions with two symmetrical vertical folds, which have a simpler shape than those of Family 2 and would then be, in reality, easier and cheaper to fabricate. The vertical folds are generated by moving the control points at the top and bottom of the module outwards (in the direction perpendicular to the vertical plane) and inwards towards the centre. This generates some permutations with different depths and different opaque to transparent ratios (figure 10). In this case, the side and top panels are assumed opaque, so the more closed configurations (which are not unlike a typical eggcrate shading device) will inevitably present lower natural lighting levels inside. However, this test was conducted to verify if there are configurations delivering acceptable sDA and ASE values thanks to the reduction of direct solar radiation coming from the sides and (to a smaller extent) from the top.

Since the configuration of the modules is symmetrical, this set of tests was applied to the South orientation only.

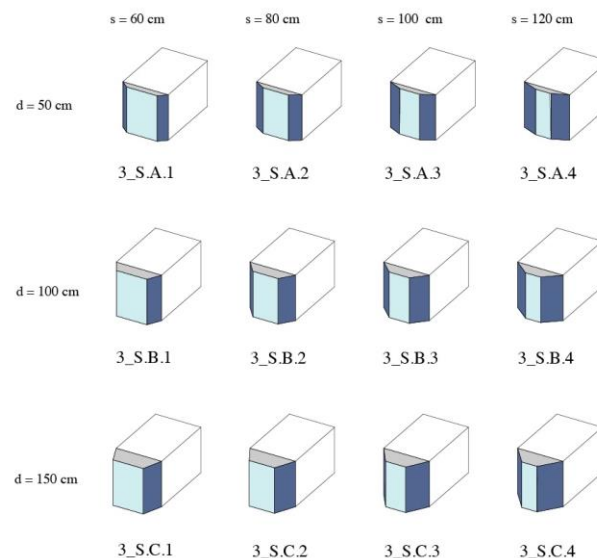


Figure 10. Geometries with variable distance of the glass pane from the structural slab (d values) and variable width of the side panels (s values).

All the variations show a similar trend of decreasing sDA and ASE values as the opaque side panels become larger (figure 11). Some of the solutions fall within the target range for both parameters, and most of them are anyway within the acceptability thresholds. It should be noted that, for the deeper

configurations (3_S.B and 3_S.C), ASE values are either very low, or even equal to 0%, because the space contained within the modular unit's thickness is not considered working space, so it is excluded from the calculations.

A comparison between Family 2 (South) and this Family 3_S shows that, for moderate ASE values (20% or lower), sDA values tend to be higher in the latter, probably because of the larger glazed area in the upper part of the panel (top transom).

In these cases, the surfaces designed for energy generation are the opaque side panels. Figure 11 shows the linear correlation between their increasing size and the amount of incident solar radiation. While this is an additional benefit of Family 3_S compared with Family 2 (South), where incident solar radiation had a decreasing trend (figure 9.a), the additional energy produced should be weighed against the increased costs for the installation of more PV panels.

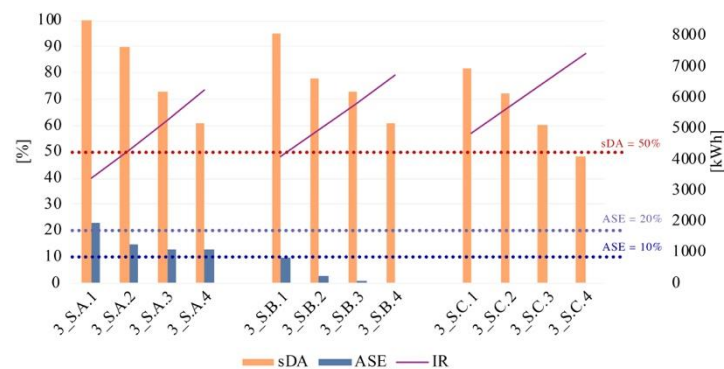


Figure 11. ASE and sDA for South orientation.

3.5. Family 3_W – one vertical fold

The fourth set of tests investigates the behaviour of solutions with one vertical fold, which would be, like those in Family 3_S, leaner to fabricate than those of Family 2 (figure 12). The vertical fold is generated starting from a flat geometry, with the half of the module transparent and half opaque (case 1). One set of solutions is based on the rotation of the opaque panel, which is always 180 cm wide and moves from an angle of 0° (flat façade) to one of 90° (perpendicular to the façade) in 15° increments (solutions 1 to 7). A second set of solutions is instead based on an opaque panel with 35° constant inclination to the façade, which starts from a 90 cm width and progressively gets larger until it is 270 cm wide, in 30 cm increments. In both series of solutions, the transparent portion of the module is the result of these geometric modifications. The top panel is assumed opaque.

Since the layout of the solutions is asymmetrical, with the opaque panel facing South and the transparent one oriented towards the North, this test was conducted for the West orientation, which would benefit of reduced direct solar gain from the South and indirect natural lighting from the North.

This set of solutions is compared with those of Family 2, series 2.1.g – 2.6.g, which were also asymmetrical but more geometrically complex.

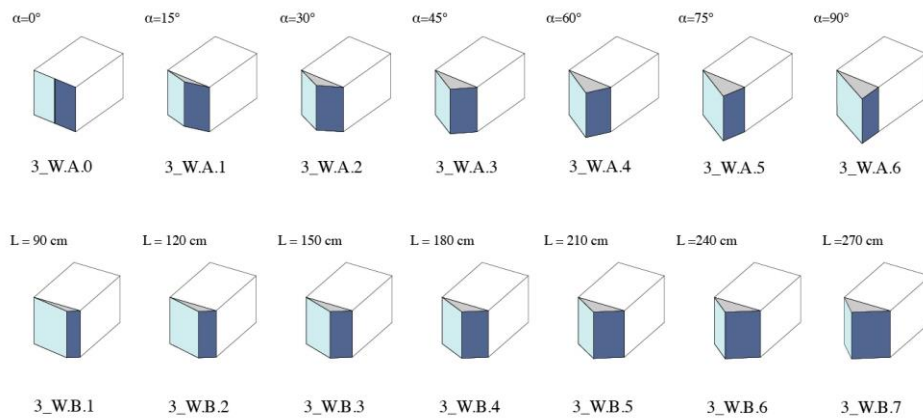


Figure 12. Geometries with variable distance of the glass pane from the structural slab (d values) and variable width of the side panels (s values).

In cases 3_W.A, the rotation of the opaque panel generates a progressively larger transparent one looking North-West: the overall effect is an increase also in the sDA values, at the cost, however, of ASE values remaining consistently above the 10% threshold – albeit within the acceptability range (figure 13). The geometric modifications of solutions 3_W.B, instead, lead to smaller transparent panels oriented North-West, with a predictable decrease in the ASE values, that anyway remain above the 50% threshold. Thanks to the shading effect of the opaque panel, ASE values fall quickly below the 10% threshold.

A comparison between Family 2 (West) and this Family 3_W shows comparable results between the latter and Family 2 cases with the transparent side panel facing North (solutions 2.1.g to 2.6.g). sDA values remain above the 50% threshold in all the solutions of the two families, while ASE values are more variable in Family 3_W. All the sets of solutions in Family 2 and in Family 3_W remain, however, within the acceptability range, so the drivers for choice could in fact be either the ease of construction, or the higher availability of solar radiation for the production of electricity (figure 13) – both favouring Family 3_W.

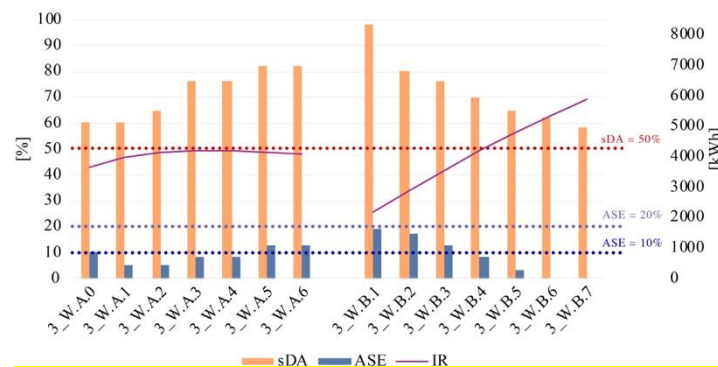


Figure 13. ASE and sDA for West orientation.

4. Conclusions

The aim of the present study was to investigate the potential of folded surface geometries alone to deliver satisfying levels of visual comfort for users, while also increasing solar potential for energy generation, as compared to a flat surface curtain wall. The initial assumption was that the articulation of facade units by way of relatively simple tessellation would be, in several instances, sufficient to meet the LEED requirements about sDA and ASE without any additional shading devices.

The investigation of various folding configurations described in the previous paragraph shows that the three-dimensional combination of opaque and transparent panels can indeed deliver much better

performances, in terms of visual comfort, compared to a flat base case. Figure 14 shows, for each family and orientation, the percentage of configurations meeting the LEED criteria of $sDA > 50\%$ and $ASE < 10\%$ and those with $sDA > 50\%$ and $10\% < ASE < 20\%$ (in the latter cases, it is expected that LEED criteria are met with minor further manipulation of the geometry).

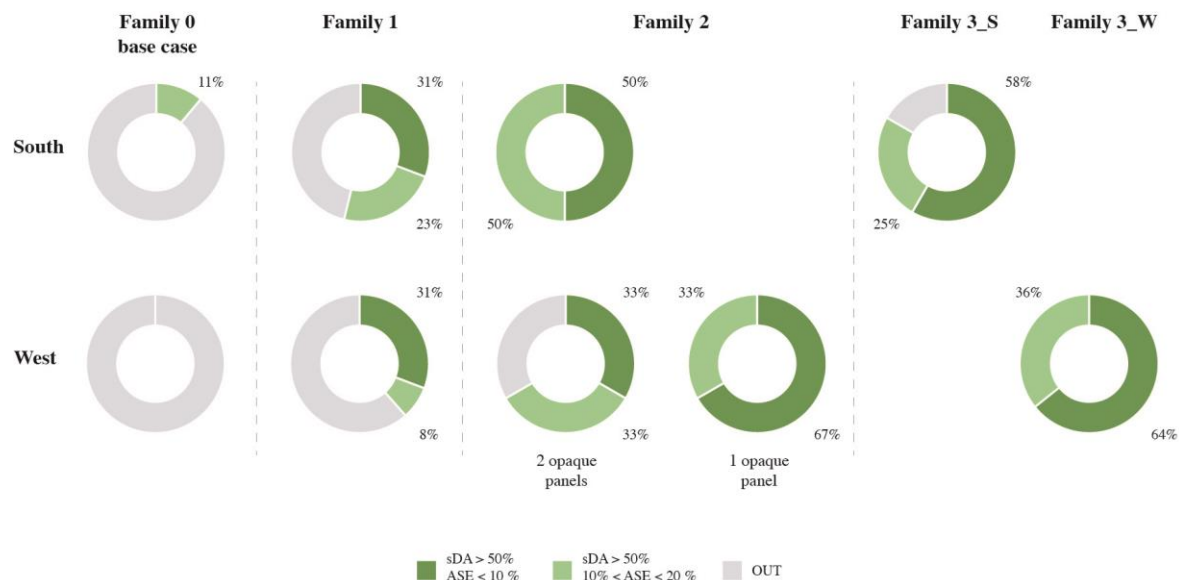


Figure 14. Percentage of cases meeting LEED criteria for each family and orientation.

Besides improving visual comfort, folded geometries provide opportunities for the installation of PV panels on surfaces that are better oriented towards the sun, hence carrying higher potential for energy production, as the analyses presented in paragraph 3 show. However, it was not always possible to have visual comfort parameters and incident solar radiation converge towards a clearly identifiable optimum solution, hence the designer will have to operate trade-offs.

The study shows, anyway, that geometric manipulation of the envelope offers a promising new design opportunity that is particularly relevant for mid- to high-rise construction located in dense urban areas, where the building's shape, layout and orientation are often determined by site constraints and legislation alone.

From an architectural standpoint, the significance of the study is twofold: firstly, it shows that it is indeed possible to identify a specific, measurable relationship between geometry and environmental performance in buildings, potentially leading toward a more responsible use of form. Further studies will have to determine whether the model is also economically viable; evaluate the impacts of tessellated geometry on heating and cooling needs; and possibly define a synthetic performance indicator integrating the latter with visual comfort and incident solar energy.

Secondly, contrary to a generalised perception of form-finding as an overly deterministic design approach, results suggest that optimisation of form can result in a variety of comparatively well-performing shapes. Indeed, energy form-finding can lead to the emergence of a new language in architecture—one that manifests information regarding the environment in ways that are intuitive and do not require mediation. Ultimately, the study opens up the possibility for tessellated glazed facades to be designed with a parametric adaptation not just to climate and orientation, but also to localised shading conditions, while at the same time providing visual comfort for the users in an extremely lean way.

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