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Computational design and parametric optimization approach with genetic algorithms of an innovative concrete shading device system

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Abstract

Office buildings in contemporary architecture usually have a high value of window to wall ratio (WWR) determining transparent façade as the most important part of the building façade to control solar gains, thermal losses and visual comfort. Therefore, in order to fulfill strict National energy regulations and LEED requirements, façades require a proper balance between transparent and opaque or shaded surfaces to avoid overheating, optimizing daylighting aspects and outdoor perception. Concrete is usually used in building sector for primary structure or secondary structure of cladding solutions. With new concrete materials and innovative digital fabrication process is possible to rediscover concrete for high performance façade/shading solutions. The aim of this paper is the development of high performance concrete static shading system using computational design approach and its optimization, by genetic algorithms, based on several parameters such as radiation control, outdoor view and daylight indexes and energy performance.

After the development of a geometry definition managed with a parametric modelling approach (Rhinoceros and Grasshopper), genetic algorithm optimization were used in order to define the openness's sizes and their cutting angle to minimize solar radiation entrance during year, maintaining outdoor view. The possible geometric alternatives were part of a sensitivity analysis with Radiance and Energy-plus engine to assess the shading system performance in terms of daylighting and energy use. In order to evaluate their performances a study case, a single office unit placed in Milan (Italy) was defined, considered with wall facing outdoors, having a WWR of 86%, and five surfaces adiabatic. The results shows that using this approach is possible to develop an effectiveness shading solution able to control radiation over the year and likewise guarantee a high performance regarding the outdoor perception and visual comfort.

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Keywords: Shading devices; innovative concrete component; computational design; genetic algorithms; form finding

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1. Introduction

The evolution of architectural style from modern architecture to the contemporary one has dramatically changed the building concept and design, especially for the building skin. However, in many case, it has led to a deficiency in terms of performance buildings and more in general of sustainable design. Consequence of this approach, according with US and European Union energy commissions, the construction industry consumes 40% of the total fossil fuel energy [1,2]. In order to address the current problem of energy consumption, national [3], international regulations [4] and environmental rating system such as LEED [5] require strict limitation in terms of thermal transmittance (U_{value} between 1.0 and 1.4 W/m^2K), solar heat gain coefficient (SHGC lower than 0.35 [6]), high level of daylight illuminance and users comfort. For instance, LEED v4 certification assigns up to three credit for daylight comfort in terms of Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). Hence, to comply with the new regulations, it is necessary to develop a skin (Complex Fenestration System - CFS) that is not only an aesthetic expression of style but also a system that assess environmental conditions such as solar radiation control, daylighting and occupants comfort.

The birth and development of computational and performance based-design have introduced new potentiality in terms of formal freedom in shape generation [7,8], flexibility and new possibilities to optimize the entire systems in terms of materials and performance controlling and data derived from different analysis [9,10]. As described in figure 1, using computational design approach is possible to realize a unique workflow, which defines all the process from the concept phase to the fabrication, taking in account the material characteristics (i.e. concrete), the manufacturing techniques and the performance target that have to be achieved.

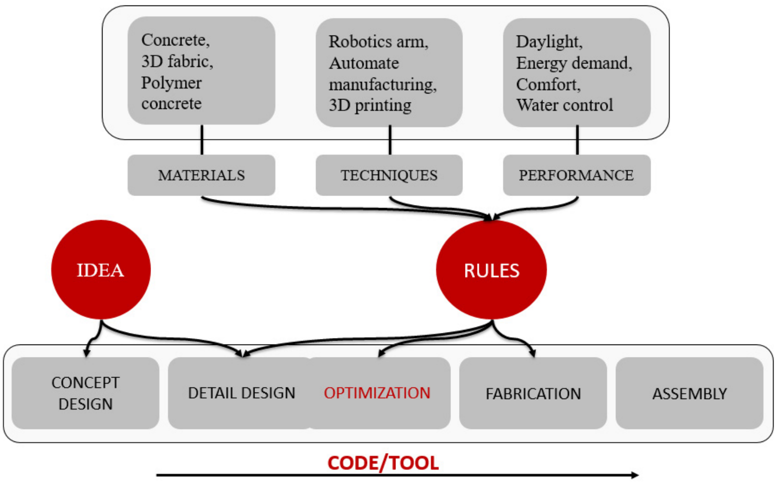


Fig. 1. Typical computational design workflow.

Once the geometry has been built depending on a sets of “rules”, the use of evolutionary multi-objective algorithms [11], [12] become essential to combine and mutually optimize all the aspects involved with the final aim to generate an optimized façade component. In the last years, several approaches have been developed and applied to buildings that used Genetic Algorithms (GA) in order to minimize total energy use depending on dimensions, shapes, orientation and window to wall ratio (WWR) [13,14] or to define the best façade solutions [15,16]. Despite of various case applied on building scale, there are only few paper on genetic optimization of shading device, in particular conducted by Omidfar [17], where GA has been used to optimize the geometry based on daylight indexes.

This paper presents a possible parametric workflow for the development of high performance concrete static shading system and its shape optimization, through genetic algorithms use, optimizing several environmental parameters. In particular, the paper is focused on the influence of different geometrical parameters of the building-shading device (such as openness factor, openings dimensions and tilt angle) on the indoor vision comfort in terms of daylighting level, glare phenomena and reduction an overall energy performance improvement. In the last part, a case study has been evaluated in order to compare the effectiveness of traditional concrete shading systems (like overhang and louvers) with the complex shading system obtained by computational design approach.

2. Design approach

At this research stage, a design flow for the development of a high-performance concrete shading system has been investigated. All the steps refers on a computational design approach in order to define and control a set of geometrical rules and data able to generate the desired façade component. These rules determine a specific system of mathematical and geometrical transformations linked to an algorithm able to produce an output according to a set of inputs and parameters. It is possible to generate a controlled system in which the final shape is strictly related to the initial idea, the fabrication process and the design objectives, considering the integration in the algorithm environment all the data from materials and specific design idea, considering the variation limits inside a pre-defined domain.

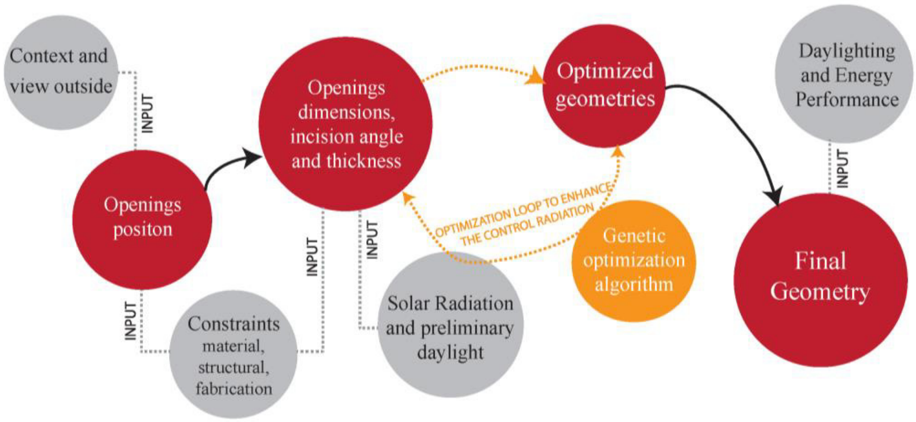


Fig. 2. Design workflow used to generate the optimized geometry based on different parameters and input.

In order to define an effective concrete solar shading system several parameters have been considered to build a customized algorithm. As described in figure 2 the first sets of input inserted in the workflow are the material properties, structural and fabrication constrains which affect the maximum dimensions and the minimum thickness of the panel. The manufacturing process used for the fabrication of this façade component consists of three phases: hot-wire robotic cut of XPS panels, thermoforming of high impact polystyrene (HIPS) formwork and concrete cast.

Once defined the size limits to guarantee the structural resistance, the tilt angles of the fins and the openings have been arranged on the shading surface, taking into account the surroundings and the most attractive visible point from the indoor (Fig. 3). Daylight preliminary analysis and solar radiation evaluation have been selected as the main parameters that influence the range variation for openings dimensions, thickness (minimum thickness set up on structural limit) and incision angles (Fig. 6b).

To select the optimal values of openings dimensions and incision angle a genetic optimization algorithm is used, to maximize the gap between the solar gains in winter and in hot season. Then, selected optimized geometries have been evaluated in terms of daylight and energy performance in order to define the best solutions.

2.1. Geometry definition

To integrate all the aspects starting from architectural design to performance simulation and managing complex shape, a unique workflow a parametric design software is required. All the procedure has been constructed in Grasshopper, a graphical algorithm plug-in for Rhinoceros.

The first step was the definition of the initial façade sample, taking into account the typical office façade dimensions and the anchoring system dimensions. In function of the building skin shape and context (other buildings in the surroundings and façade orientation), the pattern can be defined in terms of direction and density of "fins" based on random magnetic field line configurations (Fig. 3e-h). With this method is possible to generate endless combinations in order to obtain the best configuration considering both architectural aesthetic and shading system performance. The geometry structure requires incisions with stable or variable depth across the field line described previously. To control the openings pattern a bitmap-driven image approach has been used (Fig. 3a-d), through which is possible to correlate a chromatic variation to an incision depth gradient (Fig. 3i, j). The color variation form white to black, in Grasshopper definition, is converted in range of numbers able to modify the amplitude of incision (blue lines in Fig. 3j). The incision depth influences the general panel shape and modulate the quantity of light passing through the shading system.

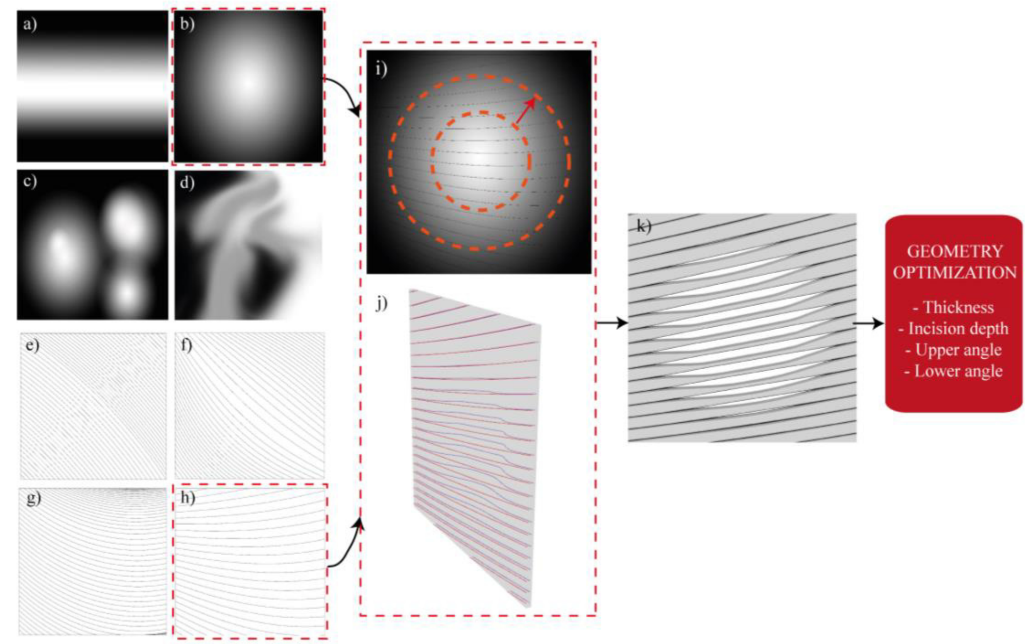


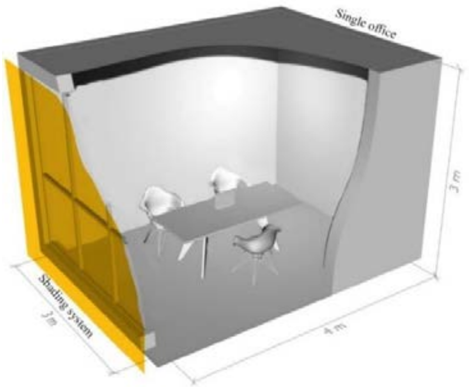
Fig. 3. Geometry generation steps (a, b, c, d) Random bitmap image to control opening position and incision depth; (e, f, g, h) Random field line pattern; (i, j) Color gradient variation that influence the openings dimensions; (k) Final shading system geometry.

The third step in geometry generation process was the definition of tilt angle of cutting surfaces. The surfaces starts from field line with the intensity given by the bitmap image, while the tilt angle can vary between 0° to 30°, both for the upper and the lower angles. This variation can also be controlled manually referring, for instance, on the sun position and the optimal angle for outside view or using bitmap-driven image. After all these parameters are defined a solid subtraction has been carried out to obtain the final geometry.

3. Calculation and models

Different concrete shading device alternatives for a unique South orientation have been evaluated for a conventional Italian single office located in Milan (45° 28' N, 9° 10' E), in the northern part of Italy, to assess the energy and daylight performance. The office were modeled in Rhinoceros and then analyzed using the Grasshopper plug-ins Ladybug and Honeybee [18] which use Energy Plus [19] and LBNL Radiance [20] such as calculation engines in order to compute the daylighting and total energy demand for heating, cooling and lighting under different complex fenestration system set-up. The dimensions of the single office are 3 x 4 x 3m (W x L x H) with only one wall (having an area of 3x3 m) facing outdoors, that have a WWR (window to wall ratio) equal to 87% (Tab.1). The internal surfaces adjacent to other offices are considered such as adiabatic.

Table 1. Single office case study - energy and daylighting parameters implemented in simulation software.



Name	***Description***	***U [W/m²K]***	***SHGC [-]***	***τ_v [-]***	***ρ_v [-]***
Ceiling	-	Adiabatic	-	-	0.80
Floor	-	Adiabatic	-	-	0.20
Internal walls	-	-	-	-	0.50
External walls	-	0.3	-	-	0.35
Glazing	LE-DGU	1.4	0.7	0.7	-
Frame	Aluminum	3	-	-	0.50
External context	-	-	-	-	0.35
Shading system	White Concrete				0.80

The simulations were realized to assess the effectiveness of different concrete shading system, changing the incision depth and tilt angles, coupled with a Low Emissivity glazing unit (LE). Table 1 shows thermal and radiative characteristic of the materials used in the simulations. The reflectance values are the typical ones, established by [21] for indoor spaces, whereas the reflectance value for a concrete shading system sample were measured with a standard Perkin Elmer Lambda 950 Spectrometer. The mean value of visual reflectance (ρ_v) obtained was equal to 80%.

The energy and daylighting simulations were performed using the same setting defined in [22].

Shading devices presented in this paper, are characterized by curved and complex shapes, due to their complexity Energy plus engine is not able to manage these types of freeform geometries. For these reason, to evaluate the effectiveness of shading device in terms of energy demand a different approach is necessary. Starting from the Omidfar's paper [17], have been developed a method based on artificial shading coefficient (SC) able to simulate the transmittance of complex shape.

Table 2. Different shading systems configuration, depending on d/D ratio.

	CS_0.5	CS_0.55	CS_0.6	CS_0.65	CS_0.75	CS_0.8
d (back opening dimension [cm])	6	8	10	12	15	17
d/D ratio	0.5	0.55	0.6	0.65	0.75	0.8
Date (day and hour considered to calculate the zenith angle)	25 Feb 12:00	21 Mar 12:00	1 April 12:00	15 April 12:00	21 May 13:00	21 Jun 13:00
Solar Elevation	33.25°	44.54°	48.91°	54.2°	64.52°	67.39°

The SC has been calculated with Daysim for every hour over the year, placing a vertical grid behind the shading system. The illuminance values have been simulated for every grid-point with and without the screen, the ratio between values resulted in hourly shading coefficient. Then the SC schedule is imported in the IDF file generated by Energy plus.

The simulations have been carried out for a concrete shading device characterized by field lines pattern in Fig. 3h and bitmap image in Fig. 3b, because of the uniformity of the pattern and openings in order to better control the parameters variation. The effectiveness of the shading system has been evaluated varying two main parameters: the incision depth (Fig. 4a), and slope of upper and lower angle (Fig. 4b). In the first set of simulation the incision angles have been maintained constant, the upper angle equal to 5° and 25° for the lower angle, value has been selected to maximize the outside view. Whereas the different openings depth (d/D ratio) have been determined for different zenith solar angles selected on preliminary energy simulation, for instance the first day with cooling loads (25 Feb) or the first peak in cooling energy demand (15 April), as stated in Table 2. In the second simulation set has been assessed in which way the slope of the lower angle can influence the results considering daylighting and energy performance. The most effectiveness configuration in the first simulation set was selected, maintaining d/D factor and upper angle stable has been changed the lower angle between 5° and 30°, each 5° step.

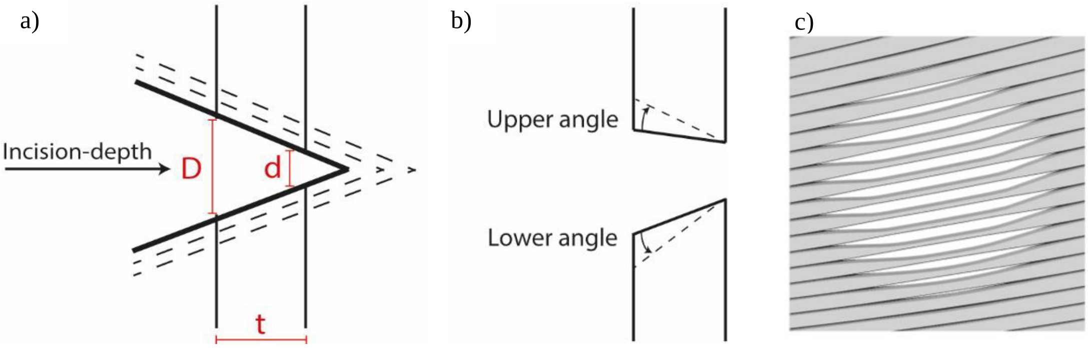


Fig. 4. Main variation parameters in geometry definition (a) Incision depth, d/D factor; (b) Upper and lower angle rotation (from 0° to 25°); (c) Concrete shading system selected for simulation phase.

4. Results – Daylighting and energy demand

In this section, the results of the simulation are reported in terms of three daylight index (Tab. 3) and total energy demand (Fig. 5) for different configurations presented in previous paragraph.

To establish the best configurations we have compared the total energy demand combined with daylighting parameters. With this approach is possible to define an energy saving solution and at the same time to guarantee an adequate level of light and view of the outdoors, avoiding glare.

In general, an interesting span of results can be observed, in terms of both daylighting performance and energy consumption. For this reason is important to evaluate which is the best and the most effective cut-off angle (d/D factor) in order to guarantee high performance level.

Table 3. Daylighting results (DA, sDA and UDI) with different shading systems configuration, depending on d/D ratio.

	CS_0.5	CS_0.55	CS_0.6	CS_0.65	CS_0.75	CS_0.8
Daylight Autonomy (DA) [%]	28	49.4	65.3	74.8	79.6	82.6
Spatial Daylight Autonomy (sDA) [%]	30	50	82	98.5	100	100
Useful Daylight Illuminace ($UDI_{100-2000}$) [%]	75.8	80.2	83.7	82.2	78.6	74.7

Analyzing Table 3 is possible to observe a normal increasing of Daylight Autonomy (DA) and spatial Daylight Autonomy (sDA) due to the greater amount of light passing through a more permeable design solution. The difference between CS_0.5 (cut-off angle 33°) and CS_0.8 (cut-off angle 67°) is quite important, with a percentage difference equal to 40%. However, considering the UDI index, that represents the percentage of hour with an illuminance level between 100 Lux and 2000 Lux, the shading system with medium permeability (CS_0.6 and CS_0.65) perform better than other solutions. This is a consequence of greater control of over-lighting time during the year, compare to most permeable solutions. By considering all the daylight indexes, the CS_0.65 configuration shows high values, both in terms of DA and UDI.

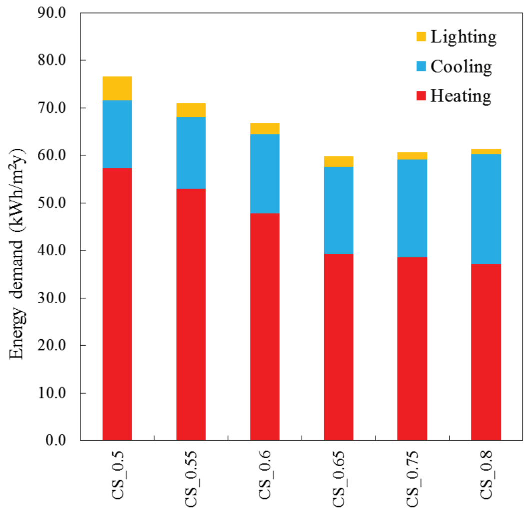


Fig. 5. Energy demand results with different shading systems configuration, depending on d/D ratio.

Figure 5 shows a non-negligible difference of energy consumptions between six different shading systems. All the solutions presented in this paper have a low openness factor to avoid glare and overheating, for this reason the impact of heating is higher than cooling and lighting. In general, the total energy demand is between 60 and 76 kWh/m^{2}y with a peak difference equal to 16.8 kWh/m^{2}y. In order to obtain an optimized shading solution, using this type of geometry, is necessary to a strike the balance between heating and cooling loads. For this reason, approach based on cooling system activation day (or week) could be an interesting method to define the cut-off angle for shading devices.

Based on energy and daylighting results the configuration that performs better than the other is CS_0.65 (concrete shading with d/D = 0.65). Indeed this type shows the best compromise in terms of total energy and lighting comfort, granting a good outdoor view.

In the second phase, we wanted to evaluate the performance varying the tilt of the lower angle. Table 4 shows that the variation of lower angle from 5° to 25° does not affect the overall shading system performance. In particular, increasing the tilt angle is possible to observe a slightly decrease in terms of daylight (DA and UDI) and same energy consumptions. According to the results, changing the "fins" slope is possible to maintain the same performance level and increasing the outdoor view.

Table 4. Energy demand and Daylighting results (DA, sDA and UDI), second simulation setup, varying the lower angle.

	CS_0.65_5°	CS_0.65_10°	CS_0.65_25°
Daylight Autonomy (DA) [%]	76.4	76.6	74.2
Spatial Daylight Autonomy (sDA) [%]	100	100	100
Useful Daylight Illuminace ($UDI_{100\text{-}2000}$) [%]	82.9	82.7	82
Total energy demand (kWh/m^2)	60.6	60.5	59.8

5. Case Study – A design proposal

After analyzing different configurations of concrete shading systems, a case study has been selected in order to assess the effectiveness of "innovative" concrete solution in comparison to traditional shading systems such as overhang and horizontal louvers. The case study used as simulation context is a famous square placed in Milan (Piazza Gae Aulenti); the area is characterized by medium high-rise office building covered with curtain wall. The single office unit (dimensions, material and systems setting described in paragraph 3) has been placed in the blue building illustrated in figure 6a, with principal façade facing south-west. In particular, the objective of this phase is to propose a new more effective design solution, using concrete shading system instead the traditional overhang built in the present situation (Fig. 6b).

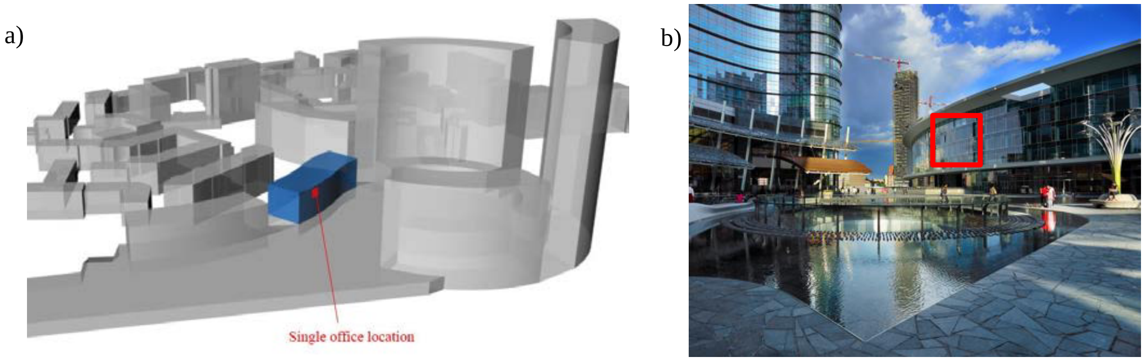


Fig. 6. Case study in Milan (a) Case study 3D model and reference office location; (b) Photograph of Gae Aulenti (photo by M. Paradisi) square and location mark.

The approach used in this research allows developing a high-customized shading system. Positioning and dimensions of the openings has been defined based on the most attractive viewpoints for the user and solar position during the year. In particular, all direct sunlight hours that could produce glare or users discomfort have been excluded, whereas in order to maximize the outdoor vision, "view" lines between eyes and attractive points (like square, park and building in front) were remained unobstructed. Openings in shading device has been controlled using a bitmap-driven image (Fig. 7a) built in Photoshop in function of two parameters described before. As shown in figure 7b the concrete shading system can be split in two main zones, the red one closer than the others to avoid glare phenomenon and the green one to guarantee the right levels of illuminance and good outdoor view. The red zone shape (Fig. 7b) has been built in function of the solar position, projected on the façade plane, which are visible by the office user.

Additional key parameters in the geometry definition are the "fins" tilt angle and the panel thickness, the right balance between these parameters allow to control the solar radiation over the year; avoiding peak in summer and permitting the radiation passing through during winter.

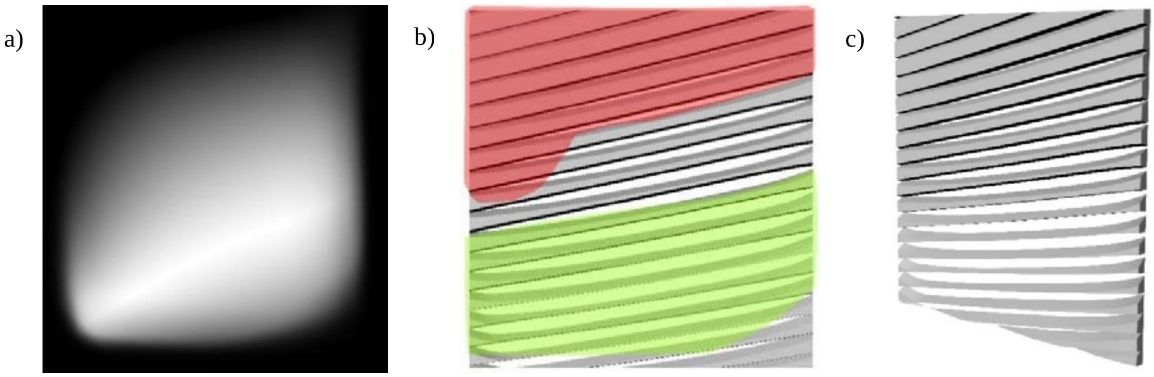


Fig. 7. (a) Bitmap image defines openings position and incision depth; (b) Front view of proposed concrete shading panel. The proposed solid zone to avoid glare is marked in Red. The proposed outdoor vision zone is marked in green; (c) Perspective view of shading system.

Proposed shading system allows modulating different parameters in function of the context and the outdoor conditions, such as solar position and radiation in order to obtain an organic façade pattern and an effectiveness solution in term of daylighting and energy demand, as proved in the next paragraph.

5.1. Case study - Results

After defining the general component geometry, as described in the previous paragraph, a multi-objective optimization by coupling Pareto front ranking and performance metric has been carried out. This approach allow investigating many design options and accelerate the design and the optimization process. In order to perform the genetic optimization has been used Octopus [23], due to its compatibility with the simulation workflow.

An optimization run were conducted with the main objective to increase the solar radiation passing through the shading system during cold season and to minimize the solar gains in summer. In total four design variables (or genes) of shading system have been manipulated, in particular have been selected the thickness, incision depth (d/D factor) and incision angles.

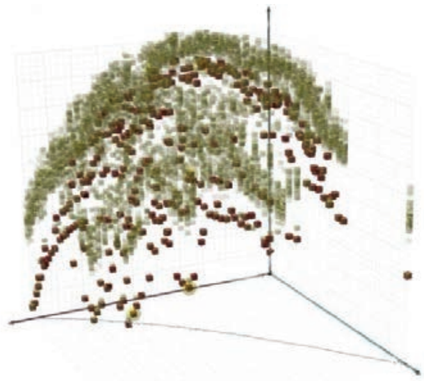
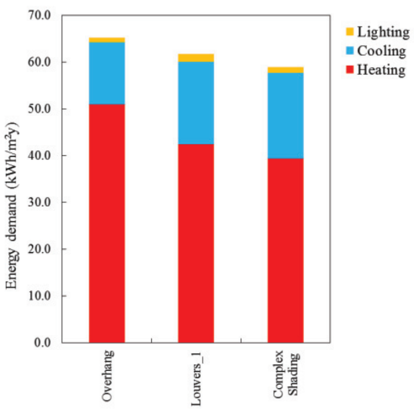


Fig. 8. Representation of genetic algorithm outputs, red dots represent possible optimized solutions.

After three thousand iterations and preliminary daylighting simulation performed on a set of solutions, an optimized solution has been selected. The shading device presents a thickness equal to 12 cm, d/D equal to 0.7 and a variable tilt incision angle from 25° to 5°. The present solution has been compared with an overhang (5 m) and louvers system.

Table 5. Daylighting and Energy results comparison between the base case (overhang) and two alternatives design proposal.



	Overhang	Louvers_1	Complex Shading
Daylight Autonomy (DA) [%]	83.3	84.6	64.7
Spatial Daylight Autonomy (sDA) [%]	100	100	75
Annual Sunlight Exposure (ASE) [%]	5.8	28.6	3.2
Useful Daylight Illuminace ($UDI_{100-2000}$) [%]	74.7	67.1	83.2
Useful Daylight Illuminace (UDI_{2000}) [%]	18.5	26.4	3.58
N° hours – Perceptible and disturbing glare	44	34	1
N° hours – Intolerable glare	64	123	10

Analyzing the results, stated in Table 5, is possible to notice a slightly decrease in total energy demand from 65.3 kWh/m^2y, for overhang design solution, to 58.9 kWh/m^2y for the optimized system. Whereas, the most important improvements have been obtained in terms of daylighting performance. Using the proposed innovative concrete shading system, the UDI between 100 and 2000 Lux increases about 20% compared to other solutions and it reduces the over lit (over 2000 Lux) hours about 70-80%. In addition is possible to significantly decrease the hours of glare during the whole year, from around 150 glare hours with classic louvers to 10 hours using optimized solution. In conclusion considering the daylight LEED index using the proposed shading system we can obtained all the credits, sDA greater than 75% and ASE lower than 10%.

6. Conclusion and future development

This paper introduces a new method for geometry generation of concrete shading solution and optimization using GA combined with detailed energy and lighting simulation. In addition, it proves that using computational design strictly coupled with robotic fabrication is possible to develop innovative and effective shading system.

The analysis shows that complex concrete shading system could guarantee a good performance in terms of daylighting and energy saving, respecting the limits imposed by regulations and rating system (i.e LEED) and increasing the visual and thermal comfort. The next goal will be the design process implementation to a whole façade system considering different patterns and the development of a new genetic optimization workflow in order to automatically optimize the geometry in function of daylight and energy performance.

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