Multi-objective optimisation of external shading devices for energy efficiency and visual comfort

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Abstract

In highly glazed office buildings, external shading devices represent a valuable option to limit solar gains and achieve better thermal performance during the summer. At the same time they impact the visual comfort of the occupants by reducing the clear view to the outside. Depending on the location of the building, maximising the external view may represent a key driver for the definition of the façade's architectural characteristics. Identifying the adequate geometry of external shadings is therefore a key aspect for the design of sustainable buildings. This article describes the application of a simulation-based optimisation tool to address this issue. Limiting solar gains and maximising the external view are two contradictory requirements, whose trade-off is investigated by means of multi-objective optimisation. Solar gains are assessed by means of dynamic thermal simulations: from the results of annual analyses, peak conditions are retrieved. For the quantitative assessment of the visual obstruction caused by the external shadings, an ad hoc script is employed. A Genetic Algorithm handles the results of these calculations and it searches for the optimum solutions that lie on the Pareto front. They all represent optimum options among which the preferred configuration can be selected during the decision making process. The optimisation algorithm, whose performance for this specific problem is validated, allows to identify the trade-off with a reasonable computational effort. From the results it is possible to determine the influence of the different variables – chosen in order to fully describe the geometric configuration of shading devices – on the balance between the two considered criteria. Calculations are run for different orientations in order to take into account the effect of variation in solar angle and exposure. In this way some general rules of thumb can be drawn for the design of effective shading elements.

1. Introduction

In designing office buildings, it is very important to limit solar gains as effectively as possible: this is because internal gains due to equipment, occupants and artificial lighting can already be very high. Only by limiting solar gains is it possible to achieve good targets of energy efficiency and to reduce the amount of carbon emissions.

These energy efficiency requirements are in direct contrast with current trends in contemporary architecture, which call for highly glazed buildings. In some situations, relying on high performance coatings on glazed elements is not enough to reduce solar gains. In these cases, using external shading devices may be a viable option. If considered properly during the early stages of the design process, shading devices can become an integral part of the architectural language of the façade. Shading devices can also be properly engineered to cut solar radiation during the cooling season, whilst allowing beneficial solar gains during winter.

Shading devices, however, do not simply limit solar gains: they also obstruct the building occupants' view towards the outside. This can be very detrimental to the value of the building, particularly if its location allows for prized views. Moreover, it can cause visual discomfort for the occupants.

It is therefore very important that the design team consider both the way shading devices limit solar gains and the amount of external view they obstruct. The main difficulty with this approach is that the two requirements are contradictory: the more shading devices there are to limit solar gains, the more they will also limit the view to the outside.

In order to design effective shading devices, it is important to consider as many options as possible.

This means that the research can be insurmountable if traditional design methodologies are employed: evolutionary optimisation algorithms offer a viable methodology, which allows for a wider spectrum of research to be made available, and, at the same time, can deal with the calculation process in a significantly shorter time. Evolutionary algorithms have been proven to be very effective in identifying optimum design solutions: they have been successfully applied to the integrated design of envelopes and building services (e.g. Znouda et al., 2007, Zhou at al., 2009, Ardakani et al., 2008), and to detailed design of façade elements (e.g. Rapone et al., 2012, Zemella et al., 2011). When more than one criterion is considered for the optimised design, two different approaches can be adopted. If a single-objective optimisation is carried out, the different criteria are assigned weights before the optimisation process (*a priori*). In the case of a multi-objective optimisation, a separate objective function is associated to each design criterion and the result is the identification of the optimum trade-off between the considered criteria. Weights to the different objective functions can be applied *a posteriori*, with no need to re-run the optimisation process (Wright et al., 2002).

Since it is not immediate to identify weights to combine solar gains and obstructed view, this paper describes a multi-objective optimisation process, carried out by means of Genetic Algorithms. The aim of the optimisation process is to identify the trade-off curve – i.e. the Pareto front – between these two contradictory requirements, expressed by two separate objective functions: annual peak solar gains and amount of obstructed view. All the options laying on the Pareto front represent optimum solutions, but they correspond to different compromises between the two objective functions. Once the optimisation process has identified all the optimum solutions, the design team can focus on them and consider other aspects, which may be difficult to quantify, e.g. aesthetical appearance, proportions with the other elements of the façade, and so on (e.g. Coley et al., 2002).

2. Methodology

For the analysis presented herein, a very generic module of a curtain wall façade has been considered. The façade module is 2.7m wide, with floor to ceiling glass 3.5m high and a slab zone of 0.5m. The 4.5m deep thermal zone considered in the calculation represents the typical perimeter zone of a building where the effects of the façade are relevant (BCO, 2009).

The research for the optimum geometry of shading devices considered a comprehensive range of different options. The following variables were considered:

- Number of louvres n: 4 ÷ 8: this dictates the spacing between adjacent louvres S;
- Rate of perforation of louvres p: 0 ÷ 50% at 12.5% steps;
- Louvres depth D: 50 ÷ 300mm at 25mm steps;
- Louvres tilt angle α: 0 ÷ 50° at 10° steps;
- Louvres inclination angle β: 0 ÷ 90° at 15° steps.

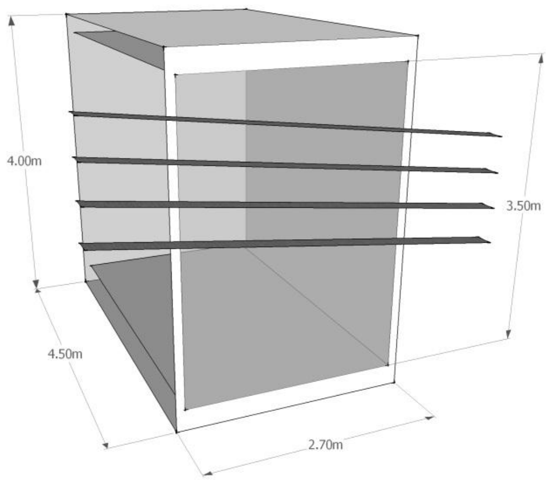

Fig. 1 – Overview of the thermal model

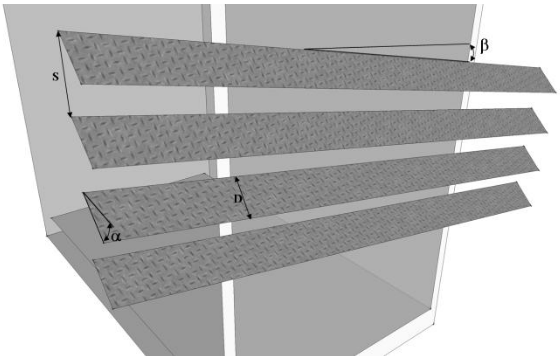

Fig. 2 – Shading devices, design variables

This leads to a total number of 11,550 possible options. Louvres are uniformly distributed along the height of the façade module, apart from the bottom 800mm, where no louvres are considered, since they would be ineffective in providing shading.

For the analysed options the following output data are calculated and represent the objective functions: peak annual solar gains and percentage of obstructed view.

2.1 Objective 1: Peak annual solar gains

The first objective function refers to the peak amount of solar gains, considering the 97.5 percentile (CIBSE, 2006). This calculation was carried out by means of annual energy simulations with the software tool EnergyPlus. Inter-reflections between louvres and between glass and louvres are taken into account. The ASHRAE weather file for London Gatwick was considered. The double glazed units considered for the vision area have a high performance coating that provides a g-value of 0.35, calculated in accordance with the standard EN 410. Solar gains are considered per unit of floor area. Calculations have been carried out for the south, east and west elevations.

2.2 Objective 2: Percentage of obstructed view

The way a shading configuration obstructs the view towards the outside was assessed by means of a script developed specifically for this type of applications. From an observation point – assumed to be in the centre of the room at a height of 1.2m corresponding to a seated position – an array of 2,500 view rays was considered, since this represents a good balance between accuracy of results and calculation time. The rays are projected on a grid evenly distributed on the plane of glass, in the area where shading devices are located (i.e. everywhere apart for the bottom 0.8m zone). If the rays lie in a direction intercepted by the louvres, they are counted as obstructed taking into account the opacity of the louvres. The percentage of obstructed view is the ratio between the obstructed rays and the total amount of rays. Figure 3 shows diagrammatically how the methodology works (only a few rays are shown for clarity). From the coordinates of three vertices of a louvre (x_1, y_1, z_1 - x_2, y_2, z_2 *and* x_3, y_3, z_3), it is possible to identify the parameters *a*, *b* and *c*, defining the plane of the louvre, by means of equation 1 – where *d* can be assigned any value. Once these parameters are known, equation 2 can be used to calculate the coordinates x_i, y_i and z_i of the intersection between the plane where the louvre lies and the line defined by the coordinates of the observation point (x_o, y_o and z_o) and of the specific point on the grid (x_p, y_p and z_p).

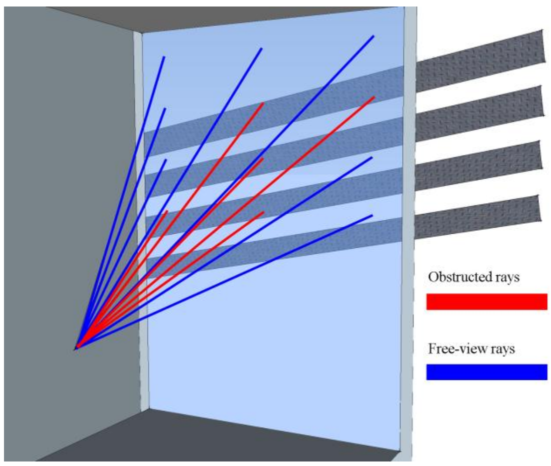

Fig. 3 – Evaluation of obstructed view

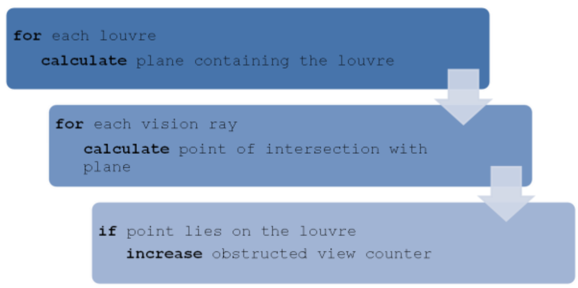

Fig. 4 – Outline of routine used to calculate obstructed view

$$\begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{bmatrix} \cdot \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} d \\ d \\ d \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} \dfrac{y_p - y_o}{x_p - x_o} & -1 & 0 \\ \dfrac{z_p - z_o}{x_p - x_o} & 0 & -1 \\ a & b & c \end{bmatrix} \cdot \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} = \begin{bmatrix} x_o \dfrac{y_p - y_o}{x_p - x_o} - y_o \\ x_o \dfrac{z_p - z_o}{x_p - x_o} - z_o \\ d \end{bmatrix} \quad (2)$$

If the intersection point (x_i, y_i, z_i) lies on the louvre, the considered ray is obstructed. This procedure is repeated for each louvre and for each point on the grid, as shown by the outline algorithm in figure 4.

This methodology is very flexible: for this paper, where general results are targeted, the grid where the “sight-rays” are projected is evenly spread across the glass. However, for project specific applications, the grid can be applied on a well-defined target, representing the most valuable view that the design team has identified in order to preserve it as much as possible.

2.3 Selection of optimisation algorithm

The simulation based optimisation problem has been solved by means of a self-developed Matlab software (Rapone, 2012), which couples the simulation program to a genetic algorithm allowing for a quick definition of the different settings involved through a graphical user interface. The interaction between the energy simulation software (EnergyPlus), the routine written to calculate the visual obstruction index and the genetic algorithm is fully automated.

A Genetic Algorithm (GA) has been chosen because of its suitability in treating non-smooth, simulation based optimization problems where the objective function is highly discontinuous and non-differentiable (Wetter et al, 2004), which is the case when it is computed by external dynamic simulations.

Genetic Algorithms are based on natural selection and genetic recombination, the processes that drive biological evolution (Darwin, 1859), and are part of the evolutionary algorithms (Goldberg, 1989), a family of population-based probabilistic algorithms that also includes PSO (Particle Swarm Optimisation) and ENN (Evolutionary Neural Networks) among many others.

In particular, a custom-modified version of the NSGA-II has been employed (Deb, 2001). The final Pareto front has been calculated on the individuals evaluated throughout all generations rather than on the last population only. This enabled the attainment of a more comprehensive and well distributed set of solutions.

In the case where the façade is oriented to the south, the whole design space (i.e. the total amount of potential solutions) was calculated in order to calibrate the algorithm and to assess its performance. A sensitivity analysis was carried out in order to estimate the values of the main parameters of the GA that guarantee satisfactory results in a limited amount of time. The aim was to achieve at least 50% of the real Pareto points after exploring no more than 5% of the whole design space, and not to miss areas of the real Pareto front: this is a simplified version of more rigorous methods (Zitler, 2003)..

Figure 5 shows the real Pareto front (in purple) and the Pareto found with the settings of the algorithm that yielded the best performance (in green). It can be observed that although there are some areas where the final solutions do not fall on the real Pareto set, from an overall point of view a good number of points of the latter are actually identified. Moreover, no areas of the actual Pareto front were missed during the optimisation process.

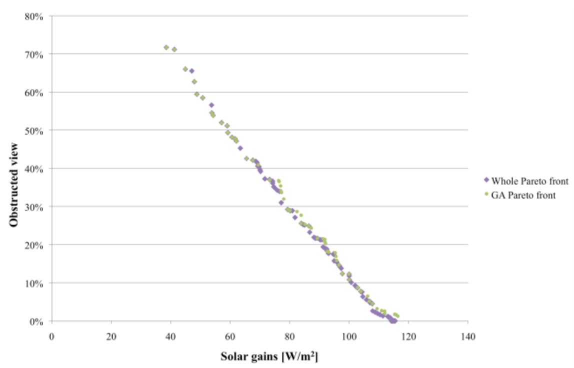

Fig. 5 – South orientation: found Pareto front and real Pareto front

According to the outcome of this analysis, the following settings for the GA were chosen: a population of 40 individuals, 15 generations, 80% crossover and 20% mutation. Since the Pareto has been calculated on the individuals of all generations, no elite children were selected to be taken from one generation to the next.

3. Results

Figures 6, 7 and 8 display the results of the optimisation process for the different orientations. The optimum combinations are represented in the solution space in order to show the distribution of the Pareto front. The charts show all the optimum options; the points highlighted in red correspond to the options which meet the recommendation of limiting the peak solar gains to less than 65W/m^2 (BCO, 2009).

It is possible to see that the BCO requirement can be met only when the external shading devices obstruct at least 40% of the view towards the outside. Moreover, for the type of glass considered (g-value 0.35), the peak solar gains cannot be lower than about 40W/m^2, and the percentage of obstructed view can be as high as 65 / 70% depending on the orientation.

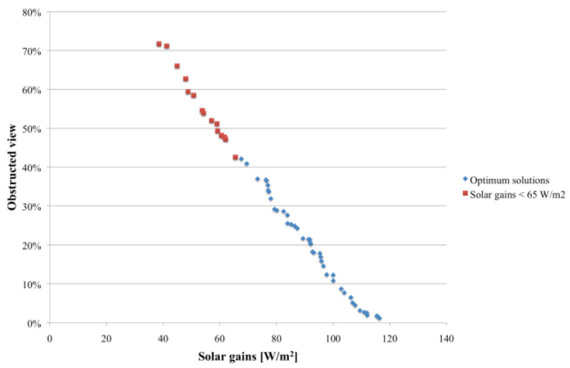

Fig. 6 – Pareto front, South orientation

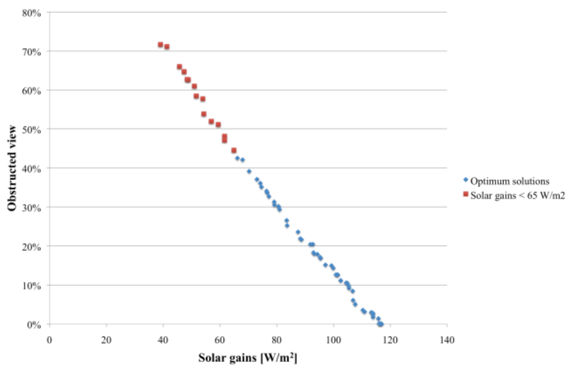

Fig. 7 – Pareto front, West orientation

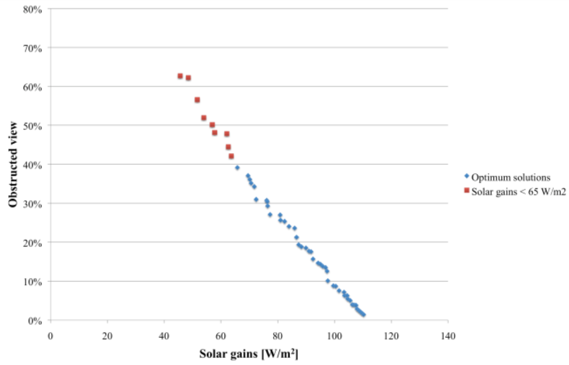

Fig. 8 – Pareto front, East orientation

This representation is valuable because it shows the performance of all the calculated optimum options in terms of the considered objective functions. In this way the trade-off between the different criteria is immediately understood. A big limitation of this representation is that it does not provide any information on the levels of the variables corresponding to the optimum solutions. It would be difficult for the design team therefore, to know how they can best develop the façade of a given project in order to achieve its optimum performance. Some works (e.g. Brownlee at al., 2012) aim to tackle this issue by providing indications of the impact that different variables have on the values of the objective functions. In this paper, we present a different approach to visualise the solution of a multi-objective optimisation procedure. The images below show the frequency with which the different levels of the considered variables occur in the Pareto front. In this way the measures that need to be considered in order to achieve optimum performance are immediately understandable. When the different levels of a variable are more or less evenly present within the Pareto front, it is possible to conclude that this specific variable has very little impact in the criteria considered for the optimisation. Therefore the design team can choose the level of this variable considering other criteria, such as aesthetics or economic reasons. On the other hand, some variables might appear in the Pareto front only with one level: in this case the design team has to accept a very definitive indication, if an optimum design is to be achieved. If this indication has implications that cannot be incorporated in the overall façade design, the whole optimisation process has to be re-thought: either the types of variables are re-considered, or the design criteria (i.e. the objective functions) have to change.

3.1 Number of louvres

Figure 9 shows the frequency with which different numbers of louvres occur in the Pareto front for the considered orientations.

Fig. 9 – Occurrences in the Pareto front: number of louvres

Within the Pareto fronts there are solutions with a good variety of numbers of louvres; generally, optimum solutions have either the minimum amount of them (i.e. 4) or 7 (i.e. the second 'most-dense' option). It is better to avoid using intermediate amounts of louvres. There is little difference among the considered orientations.

3.2 Perforation rate

Figure 10 refers to the frequency of presence in the Pareto front of the different levels of perforation within the louvres.

Fig. 10 – Occurrences in the Pareto front: perforation rate

The design team can choose among many different levels of perforation rates, even if both for south and east orientations, fully solid louvres appear to be the most effective option. For the west orientation, on the other hand, the most common solution is with louvres being 37% perforated.

3.3 Depth of louvres

The occurrence of the different depths of louvres is shown in figure 11.

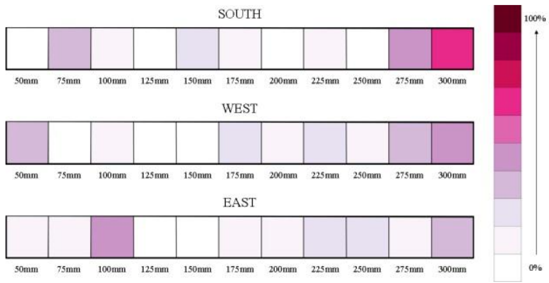

Fig. 11 – Occurrences in the Pareto front: depth of louvres

Overall, there is a relatively even distribution of different louvres' depth along the Pareto fronts corresponding to the different orientations. In general, though, it is more likely to have an optimum solution if the depth is either kept to a minimum (corresponding to solutions at the bottom right area of the Pareto front), or to have deep louvres (for the solutions corresponding to low solar gains but high percentage of obstructed view).

3.4 Tilt angle

Figure 12 shows the frequency with which different tilt angles of the louvres occur in the Pareto front for the considered orientations.

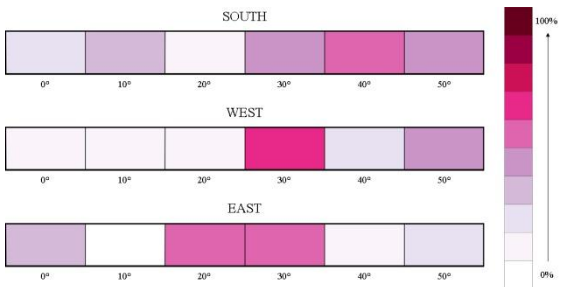

Fig. 12 – Occurrences in the Pareto front: louvres tilt angle

For this specific parameter, the results vary considerably for the different orientations. For the south elevation, there is a moderate indication for a tilt angle of 40°, but in general, all tilt angles are evenly present within the Pareto front: this indicates a weak influence of this parameter on the two criteria adopted for the optimisation process. For the west orientation on the other hand, there are very few optimum solutions for low tilt angles, and there is a strong preference for a tilt angle of 30°. On the east elevation, tilt angles of 20° or 30° are the most frequent.

3.5 Louvres inclination

The most significant impact on the overall appearance of the façade is due to the inclination angle of the louvres. Figure 13 refers to the frequency of presence in the Pareto front of the different inclination angles.

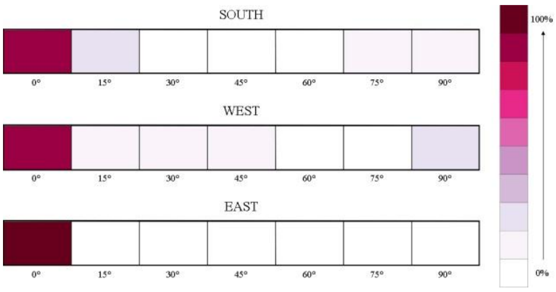

Fig. 13 – Occurrences in the Pareto front: louvres inclination

In this case, the optimisation process provides a very clear indication: the most effective inclination of the louvres is 0°, corresponding to horizontal elements. For the south and west orientations, horizontal louvres are the most frequent, but there are also other inclination angles within the Pareto fronts. For the east elevation, all the optimum solutions have horizontal louvres.

4. Conclusions

This work has presented the results of a multi-objective optimisation for the design of external shading devices of a typical curtain wall façade of an office building located in London. The calculations have been carried out for three different orientations. The trade-off between the ability of shading devices to limit the peak solar gains and their impact on view towards the outside has been assessed. Apart from the typical result output showing the Pareto front of the results space, this paper proposed a representation of results focused on the input data, rather than on the output. In this way the design team can derive more immediate answers from the analysis of results. The main indications provided by the analysis presented for the definition of the façade are:

1) For all the different orientations, horizontal louvres have proven to provide the best balance between reducing peak solar gains and keeping good levels of view to the outside.
2) For the east and west orientations, louvres have been found to be more effective when they are tilted at angles ranging between 30° and 40°.
3) In terms of louvre depth, it is preferable to have relatively large elements, or to keep them minimal: intermediate dimensions do not appear to provide substantial benefits.
4) Not very restrictive indications are given for the definition of the perforation rate and the number of louvres: the design team is relatively free to choose what best suits other considerations.

More in depth analyses of the output data are necessary to have a comprehensive understanding of the whole condition. For a specific project, it is important to consider the results on the solution space and on the input space together. Interactive tools are the most appropriate means to have a better understanding of all the information embedded in the considerable amount of data delivered during the optimisation process.

5. Future work

This paper only considered peak solar gains, therefore the focus of the analysis was on the impact of shading devices on the required capacity of the cooling system. It is also very important to assess how the cumulative solar gains during the whole cooling season are affected. It is expected that, in this case, the optimisation results will show more pronounced differences among the considered orientations.

6. Nomenclature

Symbols

n	number of louvres (-)
S	spacing between adjacent louvres (mm)
p	louvres perforation rate (%)
D	louvres depth (mm)
α	louvres tilt angle (°)
β	louvres inclination angle (°)
x	first coordinate (m)
y	second coordinate (m)
z	third coordinate (m)
a	first parameter defining the plane of the louvre
b	second parameter defining the plane of the louvre
c	third parameter defining the plane of the louvre
d	fourth parameter defining the plane of the louvre

Subscripts/Superscripts

1	of the first point
2	of the second point
3	of the third point
o	of the observation point
p	of the grid point
i	of the intersection point

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