A LIGHT-BASED PARAMETRIC DESIGN MODEL
The application of the inverse lighting in the design of the Louvre Abu Dhabi museum

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ABSTRACT: The use of a design tool materializing the performative design concept is presented. The association of parametric design with lighting intentions leads to a light-based parametric design approach. This approach have been implemented through an inverse natural lighting model which is intended to aid the daylight design (windows, shading devices or others) in the early stages of architectural design. We show this model can be used in a performative design approach to define the transparency property through a case study: the dome of the Louvre Abu Dhabi museum by Ateliers Jean Nouvel.

KEYWORDS: Natural lighting, inverse lighting, parametric design, case study

RESUMÉ : Nous présentons l'utilisation d’un outil de conception qui matérialise la notion de conception performative. L’association de la conception paramétrique aux intentions d’éclairage conduit à une conception paramétrique basée sur l’éclairage. Cette approche a été implémentée à travers un modèle d’éclairage naturel inverse destiné à aider la conception d’éclairage naturel pendant l’esquisse architecturale. Nous montrons que ce modèle peut être utilisé avec une approche performative afin de définir la propriété de transparence dans un cas d’étude : le dôme du musée du Louvre Abu Dhabi des Ateliers Jean Nouvel.

MOTS-CLÉS : Éclairage naturel, éclairage inverse, conception paramétrique, cas d’étude
1. DESIGN CONTEXT

The architectural design can be seen as a creative process intended to express an architectural position through the materialization of the designer’s intentions. These intentions have to be considered in a holistic approach but are tightly linked to the performances of the buildings. As an example, in order to achieve a sustainable architecture, designers cannot afford to take into account the natural light influence on user comfort and energy consumption. Therefore the performances of the project have to be integrated into the design process.

The performance-based design concept could help decision making in giving more information on the performance of the project. We take a light-based parametric design approach with an inverse lighting model on a real case study in order to show the efficiency of this approach. In the inverse lighting model, the opening itself is considered as an intermediary light source and the inverse simulation as an emittance research.

The Section 2 presents the use of the inverse lighting simulation in the architectural design. In the Section 3, the inverse lighting model is presented. Section 4 is dedicated to the experimental case study performed on the Louvre Abu Dhabi museum in order to compute the perforation ratio of the dome covering the museum (Figure 1), before to conclude and give perspectives in Section 5.

2. THE INVERSE LIGHTING IN ARCHITECTURAL DESIGN

2.1. Lighting performance in the design

In the performance-based design approach, the performances of the buildings, revealed by numerical simulations or scale models, are used as guidelines during the design process. Generative tools (Mahdavi and Berberidou-Kallikova 1995) and optimization techniques (Costa 1999; Kawai et al 1993) can be used to fully exploit this approach. Nevertheless, the designer has to wait until the end of the design process, or at least the end of the first iteration, to assess the performance of the project.
The key issue is to have an idea about the performances during the early stages of conceptual design, when buildings are not completely defined and when the designer can still drive his design towards his idea without a loss of time and energy. Going one step further, the building’s shape generation process can be directly driven by building performance simulations: this is the performative design concept (Kolarevic 2005; Oxman 2008).

The problem here is precisely that the project is not completely defined: How can we assess the performance of an ongoing designed project? How the simulations can play a significant role into the design process?

The parametric design defines relationships between objects. In this framework, the lighting intentions can be bound to building properties. Therefore a link can be created between the lighting and the form. Using the lighting performance of the designed project, we are experimenting the performative design approach. The inverse lighting techniques put into concrete form the performative design using lighting performance in order to aid daylight management (Figure 2). The inverse lighting techniques can be used in a performative-design approach, starting from the intention in order to define the building properties, or in a performance-design approach in order to optimize an existing project.

**FIGURE 2.** LIGHT-BASED PARAMETRIC DESIGN BASED ON INVERSE NATURAL LIGHTING: THE INVERSE LIGHTING ON THE DESIGNED BUILDING IS DIRECTLY DRIVEN BY THE INTENTION.

2.2. Design tools

Design tools are the expression means of the intentions and are adapted to the design approach: Geometrical design (Guéna 2006), Collaborative design (Halin 2003), and performance-based design (Kolarevic 2005). What is the design tool related to the light-based parametric design?

The design tool, digital or not, have to been integrated into the design process and mixed with traditional tools in order to be efficient (Stannord 1998). Each new tool brings a new design approach (Madrazo 1998). The use of a graphic tool to represent a lighting intention results in a drawing with a simultaneous expression of the lighting and the shape, although the intention is only about lighting. Therefore the designer has to use the right tool at the right
moment. The right one for the light-based parametric design allows working directly with the intention in order to compute the building properties. Therefore we are interested in the design tools in which the lighting intention can be represented.

2.3. Posing the problem of inverse lighting

The design issue is to find out the spatial configuration producing the lighting intention. The intentions have to be processed in order to compute a spatial configuration. The inverse lighting allows this processing in order to find out the source of a phenomenon starting from its effects.

Our problem is to know how the inverse lighting is integrated into the design process in order to satisfy the intention. This integration is done thanks to a new inverse lighting model adapted to the specificities of the architectural design (Tourre 2008). As the lighting sources are known (sun, sky, and reflections from surroundings) this model computes the properties of the building. Therefore the designer will be able to understand the impact of his lighting intentions onto the architectural project.

We consider that we cannot find the optimal solution with the inverse lighting model, mainly because it is very difficult to integrate in this model all the design parameters. Therefore, the inverse lighting model has to answer to the lighting problem and the results have to be interpreted by the designers in order to integrate all the other constraints.

2.4. State of the art

Designing shapes from lighting data is a well-known problem in the computer graphics community since seminal works of Poulin and Fournier (1992). Numerous methods allow the inversion of the lighting simulation and some methods are dedicated to the inverse natural lighting in architecture (Patow 2005). But no method allows working with complex features such as complex geometry, graphic lighting intention or surroundings influence.

Light-based parametric design can be focused on the building hull, which filters the natural light, or on the reflectance properties of the building materials, which influence the light transport. The problem addressed in this paper is to compute shape and light transmission properties of building openings from indoor natural lighting in buildings. This is a combination of an inverse geometry problem as we are looking for scene geometry, and an inverse lighting problem as we are looking for material properties (i.e. transparency) or light source visibility (Marschner 1998). Therefore this problem is not clearly identified in the inverse rendering framework as an inverse geometry problem or an inverse lighting problem.
3. THE INVERSE NATURAL LIGHTING MODEL

3.1. Focus on the light filter

The association of an intention with an ongoing project is considered as setting up a relationship between the outdoor environment and indoor lighting. This relation generates an opening potential and the inverse lighting is one of the means to show up this potential.

The building hull is considered as the pivot of the natural lighting phenomenon (Millet 1996). The inverse lighting principle is applied through the evaluation of the similarities between the lighting intention and the lighting provided by some elements composing the building hull. This comparison allows computing the influence of an element of the building hull in the materialization of the lighting intention.

As we are interested in lighting coming from the outside, the problem is to know if the lighted surface can see or not the light sources. This visibility is determined by the building geometric properties and so the inverse problem is an inverse geometry problem. But, looking for geometrical properties is very complex as the combinations of size, shape and position are numerous.

Nevertheless, if we consider the building hull as a light filter then the inverse problem is an inverse lighting problem. A filter can be seen as a set of intermediary light sources. These intermediary light sources have an anisotropic feature which is essential in the solving of the inverse problem. The emittance property of these intermediary light sources is bound to the transparency properties of the filter. Therefore the inverse problem can be seen as an emittance research of anisotropic light source.

3.2. An inverse lighting approach

Tourre (2008) has proposed an emittance research approach based on a pinhole model and an image distance measurement to compute the opening properties. This inverse lighting model computes the opening properties in a given space from the lighting intentions of the designer. These intentions can describe complex features with a heterogeneous distribution of light coming from the sun, the sky or the reflections of the surroundings. This model is based on a meshing of the face filtering the natural lighting (i.e. the face where the openings can be placed). Each patch is considered as an anisotropic light source and called virtual light source (Figure 3). This model has been implemented in the prototype called EEL: Espace En Lumière.
The inverse natural lighting model contains three steps (Figure 4):

- Generation of virtual light sources: the lighting contribution of each virtual light is computed in order to obtain lighting from the sky and the surrounding.
- Evaluation of virtual light sources against the designer intention: Each virtual light source is evaluated in order to compute its influence onto the lighting intention and to build an evaluation map of the filtering surface.
- Interpretation of the evaluation map: The evaluation map is considered as the input data at the interpretation step. The computed solution is intended to be a starting point for the architect in his daylight design.
4. CASE STUDY: THE LOUVRE ABU DHABI

4.1. Context

We had a great opportunity to experiment the previous inverse lighting model in the very early stages of architectural design of the Louvre Abu Dhabi museum by Atelier Jean Nouvel (AJN). This museum is a vernacular city under a protective dome which covers partially the city (Figure 1). The design team (Hala Wardé/Ateliers Jean Nouvel) wants to give a special attention to the natural lighting management under the dome. Through this study, our goal was to show that we were able to support the design team and associated engineers: Buro Happold and TransSolar.

The problem was to define the perforation ratio of the dome. The key idea is a variation of the perforation ratio, apparently randomly, but actually materializing the lighting intentions expressed by the team (Figure 5):

“Jean Nouvel formulated the main goals for the outdoor spaces with:

- a rain of light;
- variation of light levels and temperatures on the piazza;
- comfort is a part of the design” (Schuler 2008).

These intentions were associated with a temperature map under the dome in order to take into account the user comfort. Therefore the challenge was to handle simultaneously the vision of the architect and the building performances. During the study, these constraints have been translated into a natural lighting map in order to be processed by the inverse lighting model.

FIGURE 5. A PICTURE OF THE LIGHTING INTENTIONS UNDER THE DOME (©AJN).
4.2. Methodology

The process of the lighting study can be summarized as follow:

- Preliminary lighting simulations on 3D Model with Solene (2008), with and without the dome, on 21 March, June and December in order to aid the description of lighting intentions.
- Definition of the lighting intention map, which is the starting point in order to perform inverse lighting simulations.
- Inverse natural lighting with the EEL prototype (Tourre 2008) in order to compute the influence of the dome elements onto the city.
- Computing the dome perforation ratio.
- Checking the dome configuration with a forward lighting approach.

4.3. Preliminary lighting study

The preliminary lighting study showed the lighting potential of the city under the dome and the shading potential of the dome. This study defined the lighting range and therefore the value bounds of the lighting intention.

4.3.1. Irradiance values

Irradiance values on a horizontal surface for a 24° north latitude have been computed with Solene (Figure 6).

**Figure 6. Global Irradiance (W/m²).**

According to many authors (Baker and Steemers 2001; Fontoynton 1998), we consider a luminous efficiency of 110 lm/W. Therefore the maximal illuminance values are around 110 000 lux on 21 March, 120 000 lux on 21 June and 76 000 lux on 21 December. These values will be used to define the lighting intention map.
4.3.2. Sunlight duration

The sunlight duration values computed without the dome show the cast shadows (Figure 7, left). The plaza and the water area are partially protected by the buildings, even in June although the sun is very high in the sky (height 85° on 21 June at 12h00). The sunlight duration values computed with the dome show the potential protection provided by the dome to the museum (Figure 7, right). Although, the sun is moving during day and seasons, this protection remains well positioned and efficient over the main museum buildings.

**Figure 7. Sunlight duration without and with the dome on 21/06.**

The cast shadow of the dome is moving very slowly on 21 June during midday, therefore a lighting configuration computed from the lighting on 21 June will be efficient during all summer time. On the contrary, the cast shadow of the dome is moving much more during December, and a lighting configuration computed from the lighting configuration on 21 December will be efficient few hours during few days during winter. As a consequence, the lighting on 21 June is taken a work basis, while keeping in mind the impact of the dome configuration on lighting during winter.

4.4. Lighting map definition

The definition of the lighting map is essential to the inverse lighting process. This map can be defined by the architect on his own or by a collaborative design approach (our case), and can depends on other parameter (temperature in our case).

The lighting intention map contained three areas: Plaza, Galleries, Water and other buildings (Figure 8). The illuminance levels in lux were based on the report from TransSolar (Schuler 2008), meetings with the Buro Happold engineers and the preliminary lighting studies. The galleries were intended to have a daylight factor of 10%. The plaza was intended to be well protected while the
water surface and the others buildings were slightly less protected. These intentions are very complex because they are very contrasted and expected all over the year.

**FIGURE 8. THE LIGHTING INTENTION MAP UNDER THE DOME.**

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4.5. Dome perforation computing

4.5.1. Virtual light source generation

The dome was meshed in 1028 triangles as a triangle mesh is needed by the EEL prototype, and each triangle patch was considered as a virtual light. The lighting produced by each virtual light was generated using the pin-hole model of the EEL prototype taking into account the sun and the sky.

4.5.2. Virtual light source evaluation

The goal of the evaluation step is to compute the evaluation maps comparing the intentions against the lighting of each virtual light. The lighting intention map has been separated in order to compute the inverse lighting more accurately. Therefore the influence of the dome elements onto the city was computed for each area (Figure 9).

**FIGURE 9. EVALUATION MAPS OF THE DOME (L. TO R.) PLAZA, GALLERIES AND WATER AREAS.**
4.5.3. Interpretation of the evaluation maps

The evaluation maps were interpreted in order to compute the perforation ratio of the dome. The light levels given in the lighting intentions map allowed converting the influence of the virtual light in the perforation ratio of the dome. The perforation ratio of each patch was computed with a weighted sum of the desired values from Figure 8. The weights were found in the corresponding evaluation map (Figure 9). The final perforation ratio ranges from 2% to 8% over the “natural lighting” areas (Galleries), and from 0.1% to 1% over the protected areas (Plaza, Water surface and other buildings) (Figure 10).

4.6. Forward lighting simulation with Solene

In order to check the results of the inverse lighting computations, a forward natural lighting simulation was performed with Solene in which there is a radiosity engine (Figure 11). As the perforation size is small compared to the size of the dome, the perforation values can be considered as a transparency coefficient in these computations.

Although the inverse model takes into account the direct light (sun and sky), the reflections has been added to the final lighting simulation in order to assess the total lighting. According to the design team instructions, the lighting reflections were computed with a reflection coefficient of 30% for the plaza, the buildings and the dome inner face. A reflection coefficient of 5% was used for water surface reflections.

The roof of the galleries buildings has high illuminance values while the plaza, the water surface and the other buildings are well protected during summer and winter. The difference between the plaza and the water area is not visible because the desired value ranges are very close (100-300 lux and 250-300 lux) compared to the galleries expected value (10 000 lux).

The main idea of contrast between the galleries area and the others areas is well represented. We manage to get a contrast from 10 000 lux in bright areas.
to around 1 000 lux or less in darker areas. The mean squared error between the lighting intention and the lighting simulations with our dome configuration is 14.7 in summer and 19.1 in winter, which represent 5.7% and 7.4% of the maximum error value, respectively. These errors were acceptable at this stage of conceptual design and corresponded to the expectation of the team.

4.7. Discussion

Concerning the perforation ratio of the dome, the main idea of contrast expressed through the lighting intention maps is respected. The proposed perforation values have been converted in transparency coefficient in order to check the dome configuration with Solene simulations. These simulations show that the proposed perforation ratio allows approaching the lighting intentions. Therefore, we confirm the originality and the interest of this model which is able to materialize the complex intentions of the architect.

As we said in the section 2, the result of the inverse lighting has to be interpreted by the designers. Therefore, the proposed perforation ratio could be used as a basis by the design team in order to compute the geometry of the dome parts as the project is going on. As we aid the definition of the geometric properties of the dome elements directly from physical simulation, this study could be considered as a performative design approach.

Although the inverse lighting model has been designed to deal with indoor natural lighting, it fits well to outdoor natural lighting as soon as the lighting filter is well identified: the dome is this case study.

The main problem in this kind of study remains that the inverse lighting model still needs preliminary lighting studies in order to be efficient. Another drawback is that the inverse lighting computations only take into account the
direct lighting without reflections, so the lighting coming from the reflections has to be anticipated by the architect when defining the lighting intention map.

5. CONCLUSION

This work is intended to use a light-based parametric design framework implemented in a tool that is ready to use by architects and engineers. The inverse lighting model integrates anisotropic light sources and is able to define opening properties from a heterogeneous lighting distribution. The model has been tested and the results have demonstrated this inverse lighting model can be an aid to architectural design.

The interactivity of the designer is the third point allowing to characterize the digital design systems, with geometric model and evaluative process (Oxman 2008). This interactivity has to be integrated in our next research in order to fulfill the digital design systems requirements.

Where further works are concerned, others physical phenomenon can be integrated into the design process. As an example, a heat simulation could be necessary to check the impact of the proposed configuration on the user comfort (Caldas 2001). So we need to develop further models and tools that encompass the architectural design goal, the performance-based design goal and an innovative merging of both.

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