Lighting Simulation for Architectural Design: a Case Study

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Abstract

The paper considers some of the lighting simulation instruments at present available to architects for lighting design.

We study the usability and accuracy of various systems: scale models, numerical simulations, rendering programs.

An already built environment is the reference comparison for the accuracy of the simulation systems. The accuracy of the systems is evaluated for respectively quantitative simulation and qualitative visualisation. Quantitatively, the programs compute photometric values in physical units in a discrete number of points of the environment. Qualitatively, the programs generate images of visible radiation comparable to photographs of the real environment. They combine calculations with computer graphics, that is, they translate numerical values into images.

1. Introduction

This paper presents the initial results from the collaboration of a research project between the Department of Energetics and the Design Network Laboratory of the Polytechnic of Turin, Italy. The aim of the research is to analyse the possibilities of simulation of the luminous environment in the ambit of the process of architectural design, keeping in mind the importance this takes on as an element of qualification in the confined environment, in terms of environmental well-being as well as in terms of energy reactions of a building. In particular herein are presented some evaluations on the simplicity of use, versatility, and the limits of some of the simulation instruments currently available, on the one hand, analysing the possibility of modelling the lighting phenomenon and converting the information (Department of Energetics, sections 3 and 4) and on the other hand, examining more thoroughly the use of computer graphic for representing the design information into photorealistic images (Design Network Laboratory, section 5).
The overall problem was tackled using a built environment as a reference, analysed through an experimental measuring campaign, in natural as well as artificial luminous conditions. The simulation instruments used and presented in the article can be grouped into three different categories: scale models, numerical simulation, rendering programs.

2. Case Study Environment

Throughout 1996 and within the limits of a research project on illumination of internal spaces the Department of Energetics of the Polytechnic of Turin in collaboration with the Municipal Energy Company of the City of Turin developed a laboratory of illuminotechnical applications

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for the study of natural and artificial luminous environments and the implications that these involve in the relationship between architectural design and environmental comfort.

The chosen environment, made up of a comer room 8 meters in length, 6.2 meters in width, 2.97 meters in height, is formerly used as an office space, and is situated on the sixth floor of a recent building (Figure 1).

The lighting systems with which the environment is endowed, in terms of artificial (Figure 2) as well as natural illumination (Figure 3), constitute models which can easily be generalised. The artificial lighting is resolved through the use of luminaires with florescent linear sources, while daylighting is supplied by means of the glass surfaces of the two comer walls, respectively exposed northward and eastward.

3. The Scale Model

The physical scale models is the first tool used for the simulation of daylighting. There are various advantages that this instrument of simulation offer:

- it permits for the precise simulation of any, even complex, geometry;
- it allows for a quantitative evaluation of the performance of a daylighting system through the direct measuring of the significant parameters;
- it allows for a quantitative study of the lighting conditions through a direct rendering or photographic documentation;
- it allows us to observe the dynamic course of light in an environment through the use of heliodon and a system of video recording.

Below are described the stages of realisation of a scale model of the laboratory environment, highlighting the capacity and the emerged limits, in the reproduction of the environment as well as during the stages of the survey conducted on the illumination measures.

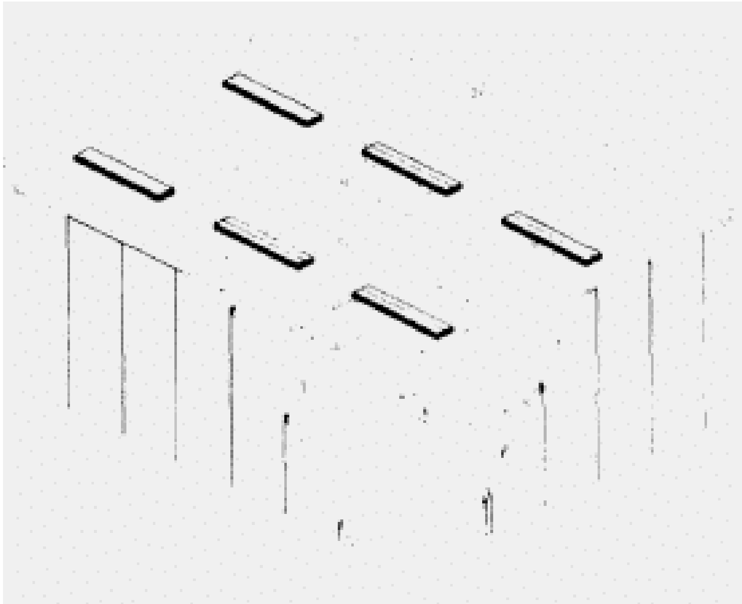

Figure 1. Isometric view of the environment.

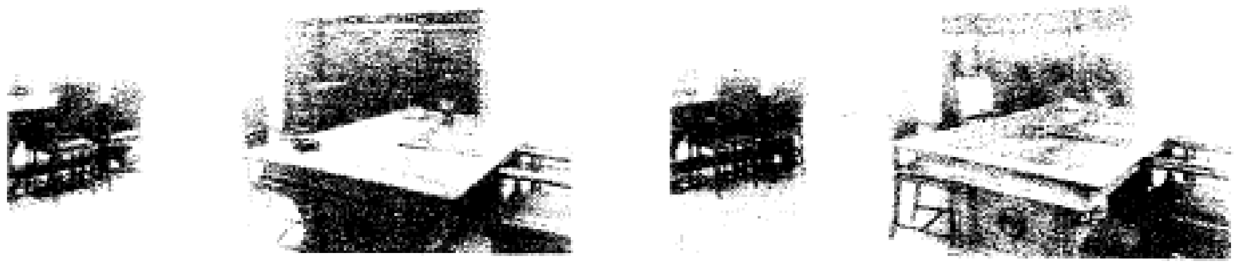

Figure 2, 3. Photographs of the built environment with artificial and natural illumination.

3. 1. Definition of the scale of the model

The choice of the scale of the model does not depend on the typical obstacles of the physical phenomenon of light distribution, but is a function of the type of data one intends to obtain and of the techniques used for evaluation. A general study on the reactions of a building in an urban context, in terms of analysing the resulting shades, does not generally require large dimensions or a particular degree of detail, while a quantitative study on the penetration and distribution of light in an environment requires a model having dimensions which permit the use of instruments internally, as well as an exact reproduction of each detail which could affect the quantitative result.

From an objective point of view of the study of the validity of the simulation instrument, in our case the decision was made to develop a model in 1:10-scale, made out of wood and exposed outdoors on the roof of a building, in a position corresponding to the referral environment.

3.2. Properties of the surfaces

In realising a scale model, it is important to exactly reproduce the superficial and photometric characteristics of the surfaces of the environment since they affect the quantity and the form of interreflection of light.

For opaque walls it is important to respect the degree of porosity and the coefficient of reflection.

We thus proceed to the in-field survey of such coefficients for each surface and subsequently to the preparation of paints which assure an equal reaction (prepared on the basis of the scale of greys of the Munsell Code).

The possibility of exactly reproducing the characteristics of the surfaces of the environment represent a great opportunity: unlike other instruments (many programs of calculation, as we will see below) scale model allows for the reproduction of surfaces with uncommon reactions, whether they are shiny or mirrored surfaces, improving the performance of the model or in terms of light distribution or the perception of the environment.

More complex is the problem of the in-scale reproduction of the glass surfaces. Above all, in the case of double-windows and treated-windows this can be difficult to achieve and in our case, as is often suggested, it was decided not to insert some transparent material, but to multiply the data of illumination obtained for the coefficient of transmission of the glass surface, having preventively measured it in the field.

3.3. Light sources

Generally, in the limits of research, simulation of the luminous environment is carried out placing the model in an artificial sky which permits us to maintain the external referral conditions constant for the entire period of experimentation, while in the case of comparison with an existing environment the model must be placed in identical conditions of illumination and thus under a real sky.

In the examined case the model was set on the roof of the building in a position corresponding to that of the laboratory environment, so that through the openings it was possible to "see" the same portion of sky dome and the same landscape.

If the possibility of carrying out simulations in real sky can represent an advantage in respect to the use of numerical models which are often not very realistic, it is also true that the scale model presents the great limitation of not permitting simulations in conditions of artificial illumination, and therefore not permitting a complete study on the luminous environment of an internal space including the effects of integration between natural and artificial light.

3.4. Survey form and results of the simulation

Having studied the stages of realisation of the model, we pass on to the analysis of the simulation procedure and the survey methodology of the quantitative data.

The parameters measured in the scale model are the same which were measured simultaneously in the real environment.

In particular, we limited ourselves to the analysis of the data of illumination taken from a few points on the horizontal plane, at work-desk height, according to a standard grid with internal planks of just over one meter (Figure 4).

One difficulty which comes up in the survey of quantitative data concerns the reduction in scale of the survey instruments. In fact, the luxmeter, placed at the same point as the scale model and the referral environment can reveal slightly different values in relation to the area it occupies in the two environments, especially when there is a sudden variation in the surroundings of the quantity of incidental light.

Specifically-studied instruments exist for using inside the scale models. Such instruments have miniaturised probes which, removed from the instrument's body can be placed on the inside of the model on horizontal and vertical planes.

From the scale model it is generally not possible to obtain a lot of quantitative information comparable to that supplied by the numerical calculation models (illuminances for very dense grids, luminance distribution, calculation of some indexes of comfort, etc.), while it is possible to proceed to a qualitative evaluation through the direct visualisation of the resulting luminous environment (Figure 5).

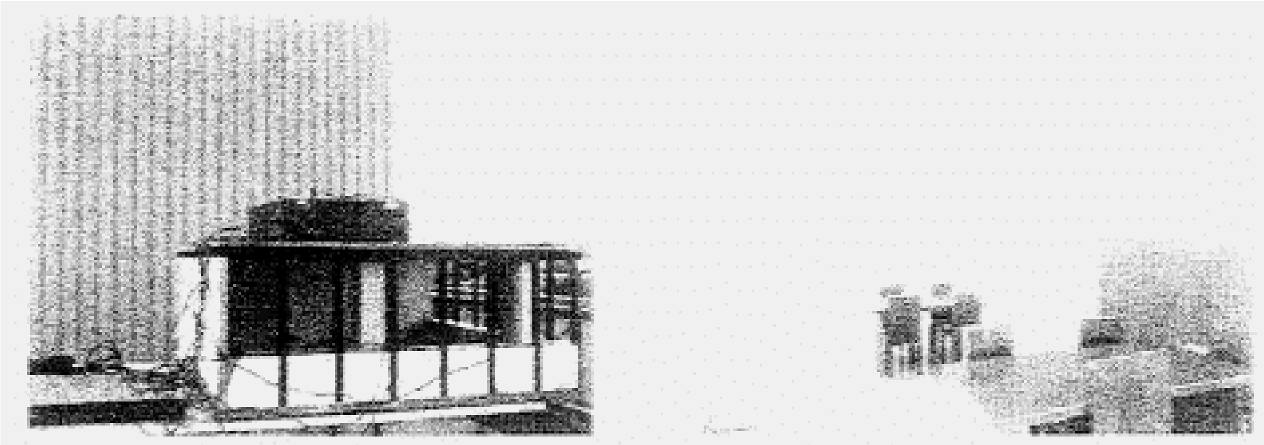

Figure 4, 5. Photographs of the scale model.

4. Numerical Simulation: Illuminotechnical Software

Illuminotechnical calculations occur through the use of mathematical models which reconstruct and quantify the overall physical phenomena which develop inside an illuminated space. Methods of manual calculation exist which permit for an initial and more general level of information, just as more advanced methods have been developed, which can only be performed through the use of computers, which produce results which supply a more accurate level of infonnation corresponding to reality.

Among the different programs of calculation analysed and verified through simulation of the referral environment, follows suite the example of Lumen Micro 6.0 (1994), a program developed by Lighting Technologies Inc., and set-up for the calculation of both natural and artificial illumination.

Before proceeding with the simulation, the program was analysed, studying the algorithms of calculation and verifying the limitations and capacities of each level of the process of simulation: both in relation to the geometry of the environment and to the photometric characterisation of the luminous sources and of the surfaces of the environment.

4. 1. Algorithms of calculation

The numerical model on which the algorithm of the program for the calculation of the direct and reflected component of light is based, originates from the method known as "flux transfer", which allows us to predict the radiative transport of the luminous flux from a source towards a receiving surface. In the simplest of cases it is possible to calculate, even manually, the illumination produced by a given source towards a point of a surface, while the program, having a more complex algorithm, permits for the calculation of lighting produced by not diffusing superficial sources towards a generic receiving surface.

For the calculation of lighting due to the indirect component, the radiative flux balances come out, following the individualisation of the radiance of each area singled-out, in relation to the coefficients of reflection and to view factors.

In the illuminotechnical calculation developed through Lumen Micro, as for many other codes of calculation, it is necessary to assume that all the surfaces are diffusing and in particular that they act as Lambertian surfaces. This represents an obstacle both in quantitative and qualitative terms, as it attributes a theoretical reaction to the surfaces that can be far from realistic.

4.2. Description of the geometries of the environment

Lumen Micro provides the geometric description of the environment through the insertion of the data on a pre-arranged worksheet, subsequently saved in the DXF format.

As well as the main walls of the environment, the program allows for the addition of internal partitions, which can be used to reproduce partitions, work-tables or furnishings.

There are limitations in the geometric characterisation of environments: all of the surfaces must be rectangular and between them orthogonal, just as each internal partition must be oriented towards a north-south or east-west direction.

From a photometric point of view, the opaque surfaces are characterised by the coefficient of reflection, with no referral to the chromatic characteristics. The description of the geometries of the environment by means of existing DXF files is limited in respect to the above-described limitations.

4.3. Properties of illumination sources

Artificial lighting sources

The availability of luminaires descriptions represents one of the most recurring limitations within the simulation of luminous environments. Many programs use the photometric characteristics of a fixed number of luminaires contained inside predefined archives.

In the case of more sophisticated programs, such as Lumen Micro, the possibility exists of increasing the number of luminaires present inside the data base, by means of ASCII files specifying the data necessary for the calculation: photometric curves for one or more planes in the space, luminous flux of the sources, position of the source, dimensions of the luminaire and corrective coefficients connected to the type of ballast.

For the simulation of the case study the photometric data relative to the luminaires installed in the laboratory room were supplied by the producing company and thus transferred into an IES file, which was subsequently loaded into Lumen Micro and used as input for the calculation.

Natural lighting sources

In the simulation of a luminous environment under daylighting conditions the problem of the characterisation of the sources (sun and sky dome) is an even more complex problem.

The amount of luminous flux which penetrates an environment is in fact connected as well as to the geometric correlations existing between luminous source and point of referral, to the radiance of the source itself.

The amount of natural light available varies continually in relation to the meteorological, seasonal and geographical conditions. In order to allow for the calculation and illuminotechnical simulation some mathematical models were elaborated which represent the distribution of light from the sky dome in standard conditions.

There are models for cloudy, partially-cloudy, clear, or uniform sky, by which it is possible to determine the internal illumination in relation to the proportion of sky dome visible from the glass surface.

For the sky-models, Lumen Micro uses experimentally-determined equations from the elaboration of data taken throughout a 60-years period in numerous cities all over the world and taken on as algorithms of calculation by IESNA (1994).

The method of calculation used to bring light into the environment is the same used in the case of artificial illumination: the sky is discretised into elements of constant luminance in respect to each point of calculation, keeping in mind, in the absence as well as in the presence of reflecting external surfaces, both of the contributions, due to the sun and to the sky dome. Despite the versatility offered by the program in terms of geometric simulation of the environment internally as well as externally, remain, in the simulation of daylighting, strong limitations connected to the rigidity of the sky models used, which directly supply the values of illumination in relation to the latitude, longitude, day of year and time of day, without permitting the use of specific data of the locality being examined, or the data taken in the field.

4.4. Results of the simulation

As a calculation output most of the programs of simulation of the luminous environments supply a more or less complete group of quantitative and qualitative data.

Currently the most advanced software permit, faced with a certain simplicity of use, the acquisition of various types of output: horizontal and vertical illuminance, exitances or luminances of the surfaces of the environment, glare indexes, comfort indexes, etc., and relative representation in the form of iso-curves.

In some cases there is also the possibility of obtaining results of the simulation in the form of a realistic image of the environment examined, thus opening up new perspectives in the field of verification of visual comfort and getting nearer to perceptive results usually only obtainable through the use of an in-scale model.

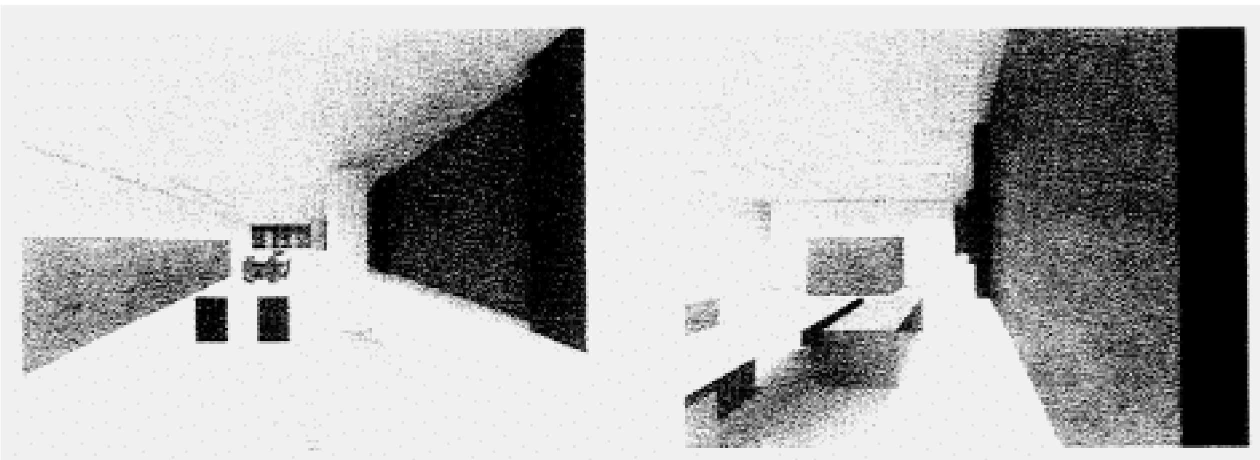

Figure 6, 7. Lumen Micro synthetic images.

of a scale of greys, the actual distribution of luminances from a variable point of view through the navigation inside of the environment. (Figure 6, 7)

5. Rendering Programs

Today numerous programs for rendering the interaction between light, form, colour and materials are available. Our aim is realism, that is to bring about renderings comparable to reality, to the built environment.

The comparison between the various programs is based on the analysis of the different mathematical models implemented. Substantially the mathematical models used today go back to Gouraud and Phong, Ray-tracing, Radiosity (Caneparo 1995).

Gouraud (1972) and *Phong* (1975) consider the lights as point sources. The intensity of light received form a point on the surface of the object is subdivided in the contributions respectively of ambient, diffused and reflected light (1).

$$(1) \quad I = I_a + k_d \sum \overline{NL_j} + k_s \sum \overline{NH_j}$$

Ray-tracing (Whitted 1980) traces back the route followed by each single ray of light. The route of each ray is traced from the point of view across the projection plane to the object, and, if the surface material is reflecting or translucent, the tracing goes back to another object, and so on until the ray is originated from the light source. Substantially, Ray tracing calculates recursively the integral equation (2) for each point.

$$(2) \quad L_{ij} = L_{ij}^{E} + \sum \int R_{kij} L_{ki} A_{ki} G_{ki} dS_k$$

Radiosity (Goral et al. 1984) considers each surface as part of a Lambertian body. The equation system (3) represents the interchange of energy reflected and emitted in the environment. Solving the system offers a discrete representation of the diffuse shading of the scene.

$$(3) \quad L_i = L_i^{E} + R_i \sum L_k \int A_{ki} G_{ki} dS_k$$

We prefer the ray-tracing algorithm because Gouraud and Phong, to improve computational efficiency, deal exclusively with direct illumination plus an ambient factor. The radiosity algorithm considers objects as Lambertian (i.e. diffusive), ignoring specular highlights and reflections, which in many practical cases contribute significantly to the overall illumination.

An other relevant aspect for the choice of the program is the possibility to use absolute values in physical units. Between the ray-tracing programs, the Radiance package gets its own name from the measuring unity of the radiometric equivalent of luminance measured in watts instead of lumens.

The complessive process of simulation of a built environment with Radiance can be broken down into the following steps: the geometric description of the environment, the formalisation of the properties of the materials, the individualisation of the physical and photometric characteristics of the luminous sources.

5.1. Description of the geometry of the environment

There are numerous computer aided design programs which facilitate the description of 3dimensional objects in space. Among these, AutoCAD from Autodesk Inc. is one of the most popular and its use in creating a model of the environment can be representative of a more general praxis. The 3D model describes the main geometries of the office, even if for reasons of time and resources the representation of the furnishings is simplified (Figure 1). The only specific criteria used in the realisation of the model is to ascribe each material of the room its own layer.

An important factor for the usability is the possibility of directly acquiring geometries of any complexity automatically. In our case the DXF (Amor 1990) and Torad (Mischler 1993) translators have demonstrated to be able to convert directly from AutoCAD to Radiance, without any specific user's intervention.

5.2. Physical properties of surfaces

Radiance has predefined properties of some materials: plastic, metal, translucent, mirror, dielectric, glass, or the bi-directional reflection transmission distribution function (BRTDF) of a material. The descriptions are usually personalised in order to represent the specific characteristics of the specific objects inside the category which defines them. For example, for "plastic" materials the colour, through the red, green and blue components, the specularity and the roughness are definable.

The factor of reflection is known for most of the materials in our environment, as they have been measured, while the chromatic values have still not been measured. Therefore, at the moment the colour of each material is determined empirically in such a way that the average of the values for the red, green and blue coincide with the measured factor of reflection.

5.3. Characteristics of light sources

The intention is to verify the data of the simulation of natural as well as artificial light. The simulation of natural light is based on standard CIE sky models. In order to improve the approximation for the conditions of this site, we expect to subsequently integrate the standard CIE data with the values measured in the field.

For the artificial light the IES description of the light sources formerly used for simulation with Lumen Micro are acquired and converted. The chromatism of the light sources, measured in the field with a colormeter, integrates the IES data of the geometry and the photometric characteristics of the light sources.

5,4 Results of the simulation

Quantitatively, Radiance, like the other numerical tools, provide photometric values in physical measurements for a discreet number of points of the environment. Quantitatively it generates representations of the luminous environment in the form of images comparable to photographic shots of the built environment.

For the specific case being analysed, the comparison between the measured and simulated data will be interpreted as the reliable index of the quantitative estimates of the specific program.

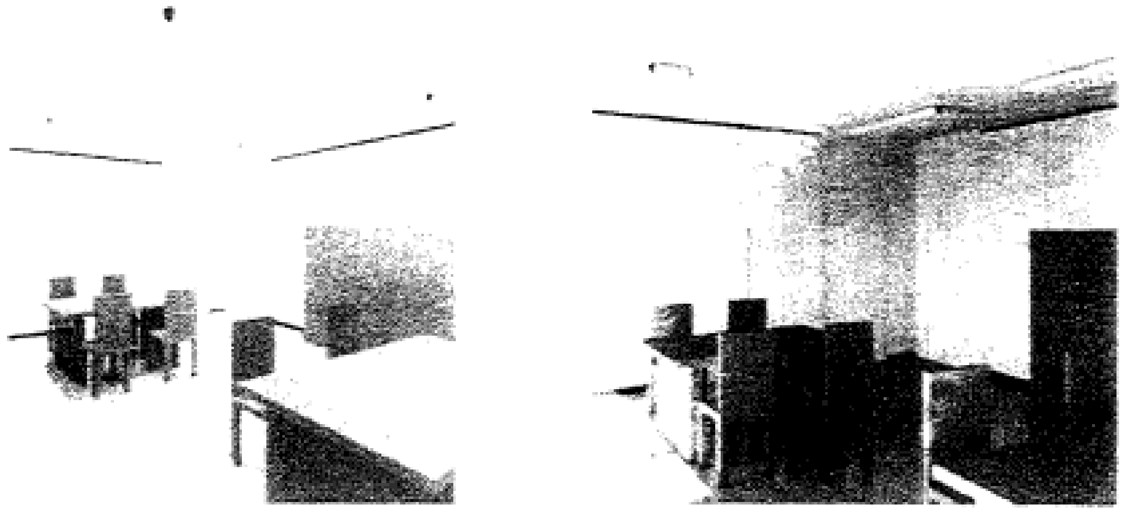

Figure 8, 9. Radiance synthetic images with artificial and natural light.

The verification of the qualitative estimate is, on the other hand, based on the comparison between respectively the virtual and the real images of the environment (Figure 8, 9).

The comparison between images is still essentially entrusted to subjective criteria, even if techniques of images metric mediated by cognitive psychology and image compression literature (Meyer et al. 1986) (Rea and Jeffrey 1990) (Rushmeyer et al. 1996) are beginning to be available. The results are, if not an effective and completely-reliable indexes, at least some indication of the visual quality offered by the simulation.

5.5. Note on collaboration through networks

The computer networks have made it possible to participate in the research specific competence, even from remote sites. For the simulation of natural illumination with Radiance we collaborate with Dr Joven Ignacio of the ECADAP Group at De Monfort University. FTP connections make possible the sharing of the model file in almost real time. Practically, on a FTP server we define a common directory through which, as the project proceeded, we are able to share the results of the simulation.

The files of the 3-dimensional computer model, the descriptions and the procedurals of the materials, the descriptions of the sky and of the luminaires and finally the results of the simulations themselves in different conditions and with different parameters are made accessible to the entire research group. Furthermore, through e-mail we frequently up-date on the progress of the research. In fact, problems, directions and questions, arising during the course of the simulation, are rapidly shared through e-mail and in this way often resolved. In some cases, the rapidity of electronic mail made it possible to get an immediate response to a question, comparable to a direct discussion. To the extent that for the entire duration of the project only once is felt the need for direct communication: a phone call!

6. Conclusions

The comparison between the different instruments of simulation will be completed, having terminated the elaboration phase of the quantitative data, through an analysis of the main photometric parameters surveyed in the environment.

Setting-up programs which bring about physically-based renderings have three relevant consequences. Firstly, simplicity: programs of simulation which are accessible and simple to use permit for an extensive use of the simulation in the practice. Secondly, versatility: the programs permit for simulation of the different components of illumination and different types of illumination, including natural, even in geometrically-complicated environments. Consequently, it becomes possible to design more energy-saving environments, having a better visual quality and comfort. Thirdly, qualitative: some programs integrate the qualitative with the quantitative, the simulation with the rendering, that is, they combine calculations with computer graphics, translate the numerical values into images. This implies for the designer another level of representation-comprehension which predicts the qualitative and illustrates the quantitative.

Acknowledgements

We must offer our special thanks to: A.E.M. (the Municipal Energy Company) for the availability of the test site; Autodesk Inc. for having given us the possibility of using AutoCAD; Massimo Desalvo for the images from Lumen Micro; Livi Tecla for 3D modelling the room with AutoCAD; Greg Ward for the Radiance package; Joven Ignacio for the advice in simulating the daylight conditions with Radiance.

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