COLOR, MATERIAL AND LIGHT IN THE DESIGN PROCESS – A SOFTWARE CONCEPT

Christian Tonn[1], Dirk Donath[2]

ABSTRACT

The paper describes a concept for the IT-support of efficient and plausible planning with color, material and light in the architectural design process. The “Colored Architecture” software prototype described in the paper is a modular part of current research activities at the Bauhaus-University Weimar. In addition to special tools and forms of visualization, the paper describes a concept for the fast, realistic, parameterized assessment of the factors color, material and light in architectural modeling. The traditional rendering of architectural models using radiosity light visualization is often too time-consuming to be used in the design process. To improve the workflow, the radiosity visualization described provides a physically correct visualization of the material whilst allowing the parameters color, material and light to be adjusted interactively. The “Colored Architecture” prototype is an integrated component of the Building Information Model and supports the professional planning of color, material and lighting concepts in architectural design.

KEYWORDS

caad, design, interactive radiosity evaluation, color and material design, skylight

INTRODUCTION

The tools used by professional color and interior designers are not yet adequately supported in the IT-environment. Instead only insular solutions exist for architectural visualization, presentations or complex physical light simulation. The software prototype “Colored Architecture” addresses this deficit and supports digital planning with color and materials from the initial design, through the planning phase to specification.

In practice environments digital color is not yet regarded as sufficiently accurate or reliable, with the result that tools for color or material design are rarely used. However, with the advent of new affordable color calibration tools for monitors (e.g., ColorVision Inc. “Spyder2” 2004), beamers (e.g., Bimber et al. 2005) and printers (e.g., Richter 2005) the IT-supported design of color and materials has become a realistic proposition. The planning of color and material concepts requires considerable

1 Research Scientist, Chair for Computer Science in Architecture, Bauhaus-Universität, Belvederer Allee 1, Weimar, 99423, Germany, Phone: +49(0)3643/584206 FAX +49(0)3643/584202, christian.tonn@archit.uni-weimar.de

2 Professor, Chair for Computer Science in Architecture, Bauhaus-Universität, Belvederer Allee 1, Weimar, 99423, Germany, Phone: +49(0)3643/584201 FAX +49(0)3643/584202, donath@archit.uni-weimar.de

experience, background knowledge and vision and is usually undertaken by specialists. It requires good knowledge of how light, material and color interact with one another and the resulting spatial impression. In particular younger planners, students and lay people have little experience of the visual and aesthetic characteristics of colors and material surfaces. The widespread use of white in interiors begs the question whether white truly represents the taste of the inhabitants or that of the interior designer or whether this is simply an indirect result of the complexity of color design. To be adopted in practice a tool must therefore offer simple, plausible and above all reliable support for a planning task. This paper aims to show that through specific IT-support of this area, the design of color and materials in architectural environments can be undertaken with greater confidence.

THE DESIGN OF COLOR AND MATERIALS

In this approach the choice of color and materials in architectural environments is a three-tier process:

- the color and material design concept,
- assessment and evaluation, and
- realization/implementation.

A number of different concepts for these stages of the color and material design process have already been elaborated (e.g., Donath et al. 2004).

The design process depends largely upon the expertise, experience and knowledge of the designer. As such, the digital support of this process supports and adapts existing strategies, instruments and representations, e.g. alternative variants, color studies and color relationships such as harmonies and contrasts.

The assessment and evaluation of the design is undertaken using elevations and perspectives from the 3-D model. A further useful representation, particularly for editing, is the 'unfolded' 2D interior elevations of a room including floor and ceiling. To reliably assess and evaluate the results of color and material choices, integrated radiosity visualization is employed as it is able to represent interactions between different surfaces, e.g. reflections. Of particular relevance here is the visualization of daylight. The sun is not regarded solely as a single light source but as a diffuse source – the sky lights up the model from all directions. 15 predefined CIE sky types are included in the software, which, depending upon position of the sun, cloud cover and atmosphere, exhibit different irradiation properties.

For the realization of color and material concepts in practice, room color cards, sample printouts and on-site color projection using SmartProjectors (e.g., Bimber et al. 2005) are supported.

ASSESSMENT AND EVALUATION OF COLOR AND MATERIAL

The software prototype "Colored Architecture" was developed to support the color and material design process (Tonn 2005 and Tonn et al. 2006). Initial tests quickly showed that assessment of color and materials was best achieved using radiosity-based visualizations as they can simulate the effect of light, materials and color of nearby surfaces in their built environment much better than assessing the pure colors or materials in catalogues or swatches.

A central problem is that the calculation of radiosity visualizations using current hardware can be very time consuming. In the experimental process of the design and assessment of color concepts such delays are counterproductive to workflow.

Radiosity computation is used to visualize the impression of an environment taking into account the parameters light, geometry, color and material characteristics. The calculation of mutual interactions between individual objects in a scene is the most time-consuming aspect of visualization. However, in the color and material design process, the geometry of the architectural model is rarely changed. As a result the process can be optimized by pre-calculating the geometric interdependencies. This paper examines a radiosity approach which allows the parameters 'position of the sun', 'illumination' and 'materiality' to be varied after an initial radiosity calculation has been undertaken, and so enables the interactive design and assessment of color and material concepts.

RELATED WORK

Radiosity light distribution computation is an integral component of commercially available visualization programs such as Cinema4D (Maxon Computer Inc.) or 3D-Studio (Autodesk Inc.). However, when material or lighting conditions are adjusted, these systems must undertake the entire radiosity computation from the beginning to produce reliable results.

Fast real-time visualizations using "Relightning" (e.g., Pellacini et al. 2005) or "Precomputed radiosity" (e.g., Sloan et al. 2005) are currently the subject of much research in the field of computer graphics. In particular in the film and computer games industry, new techniques are being developed that capitalize upon the growing performance of modern graphic cards with hardware-accelerated 3D-graphics visualization. The market availability of high-performance graphic cards is becoming more affordable and therefore feasible for everyday planning tasks in the architecture office.

The use of a "skydome" reflecting changes in position of the sun, cloud cover and atmosphere as a means of representing the sky as a light source for architectural visualization was proposed in 1994 by Dobashi et al. for interior and outdoor environments (1996). After an initial visualization, the parameters light and surface color could be varied and displayed without the need for high processing requirements. In Dobashi's example changes to material properties do not affect the surroundings in terms of reflected light and color.

Building upon Dobashi's work, the system described here aims not only to accommodate changes to lighting conditions but also changes to material properties such as color, reflectivity, and transparency. The effects of such changes should be visualized in real time without long delays for the purposes of color assessment.

ILLUMINATION MODELS AND COLOR SYSTEMS

A number of different illumination models exist to describe materials and their optical characteristics, e.g. Lambert and different BRDF light models (e.g., Schlick). The "Bidirectional Reflectance Distribution Function" (BRDF) is the most physically accurate descriptive model. According to this model, the reflective behavior of light is determined by physical components such as the angle of incidence of light, the wavelength of light, the exact position on the surface of the material and the materiality of the surface described as a series of optically active layers.

As with illumination, a number of color systems exist for representing the color of a material. Most well known are RGB, sRGB, CMYK, CIE-Lab, CIE-XYZ and the physical color spectrum diagrams. Many manufacturers often provide color swatches in one of these color systems to aid their use in digital planning tools. Colors can be converted between color models, with some limitations such as the size of color space or with the help of additional parameters such as the conditions of the light under which they are viewed. In his article "Comparing Spectral Color Computational Methods", Hall (1999) describes the sRGB ("normalized RGB") as one of the better models for radiosity visualizations. This color system is based upon combinations of Red, Green and Blue colors normalized according to a D65 white balance and a standard gamma of 2.4. This standard is used by most computer operating systems and therefore obviates the need for color conversion. The sRGB color system was therefore chosen for the following visualization computation.

CALCULATION CONCEPT

Radiosity computation was first put forward in 1984 by Goral et al. (1). Rays of light meeting a surface are not only reflected but also radiate diffusely from rough surfaces. Goral's approach used so-called "Lambertian reflectors" in which reflections radiate evenly in all directions. As the surfaces of three dimensional geometric models are not evenly illuminated due to shadows, covered areas and diffuse irradiation from other neighboring surfaces, surfaces are divided into many small "patches", the size of which is determined by the desired degree of precision. The computational problem consists of deriving an equation and an unknown per patch. The Radiosity equation put forward by Goral et al. (1984, equation 6) is as follows:

$$B_j = E_j + \rho_j \sum_{i=1}^{N} B_i \cdot F_{ij} \qquad \text{for} \qquad 1 \le j \le N \tag{1}$$

B_i, B_j	radiosity of surface i or j	[W/m²]
E_j	rate of direct energy emission from surface j	[W/m²]
ρ_j	reflectivity of surface j	
F_{ij}	form factor between surface i and surface j	
N	number of surfaces	

Different approximation procedures exist for calculating the form factors F_{ij} between patches. The form factor between small and distant patches (unobstructed) an be calculated as follows:

$$F_{ij} \approx A_i \frac{\cos\phi_i \cos\phi_j d_{i,j}}{\pi \cdot r^2} \tag{2}$$

A_i	area of surface *i*	[m²]
φ_i, φ_j	angle between the normal of the surface *i* or *j* and the connecting line between the centers of surfaces *i* and *j*	
$d_{i,j}$	visibility between the centers of surfaces *i* and *j* : $d_{i,j} = 1$, if the center of surface *j* is visible $d_{i,j} = 0$, else	
r	distance between surface *i* and surface *j*	[m]

The direct resolution of the entire computation requires the computation of form factors F_{ij} between all the patches. Modern radiosity algorithms use different approximation approaches such as "progressive refinement" (e.g., Cohen et al. 1988) and "hierarchical radiosity" (e.g., Hanrahan et al. 1991) to speed up the process. The most complex part of radiosity visualization remains the computation of the reciprocal visibility $d_{i,j}$ of the different patches.

As described above, the radiosity computation of the color and material design process can be optimized. An initial radiosity computation is used to establish the pattern of radiosity but with the exception of absolute luminance and color values. This pre-visualization determines the radiosity equations and saves them with their computationally-intensive geometry-dependent aspects and references for the material and light source variables. In a second process (the design and assessment process) these variables are varied and can be computed in a comparatively short period of time.

In the approach described we have assumed we are dealing with "Lambertian Reflector" surfaces. In the architectural design process, surfaces do often have diffuse reflective characteristics, e.g. plaster, matt paint, wallpaper, carpets, wood or concrete. Later in this paper we will discuss the use of the more precise material-related BRDF illumination model with the above approach.

THE PROPOSED ALGORITHM

The computation process can be structured as follows:

1. Generation of a hierarchical sky illumination.
2. Generation of patches from the geometry of the architectural model.
3. Direct illumination of all patches.
4. Iterative light exchange.

SKY ILLUMINATION

Radiosity computation is essential for the design of interiors under daylight conditions. The interior is illuminated by colored light from all directions of the “skydome” (e.g., Dobashi et al. 1994) depending upon cloud cover, atmosphere and position of the sun. However in contrast to Dobashi’s suggested approach, the color and material component of light reflections between surfaces within the model are also important for the accurate depiction of architectural interiors. If strong light shines into a room through a window, the reflection of the light falling on the floor or the wall illuminates the rest of the room. The color of the materials affects how the lights is reflected and can have a significant impact on the overall appearance of the interior. This effect can be seen particularly well with colored window jambs (Figure 1).

Figure 1: Colored window jambs reflect light and affect the overall appearance of the interior

According to the precision required for global illumination, the "skydome" is mathematically subdivided into individual sub-surfaces, each represented as a point-light source. If the position of the sun, cloud cover or the atmosphere changes, the coordinates of the point-source remain the same – only the light properties of the source change, the geometry remains constant. To simulate the effect of the movement of the sun, the resolution of the “skydome” must therefore be sufficiently fine.

At a resolution of approximately 1° the “skydome” is represented as 15440 individual sources of light. However, where a single surface is exposed to the sky as a whole, it would be unnecessarily complex to compute its illumination by all 15440 sources. By establishing a hierarchic approach to subdividing the “skydome”, processing load can be reduced significantly. The triangular subdivisions of the “skydome” icosahedra-hemisphere are increasingly finely divided according to the level of hierarchy. According to specified error tolerance levels, coherent groups of “skydome” light sources can be mathematically grouped into a single light source of the next higher hierarchical level (e.g., Hanrahan et al. 1991) (Figure 2). As a result only a few point light sources are necessary to compute the direct illumination of each patch. Likewise other approaches such as “spherical harmonics” (e.g., Sloan et al. 2002) can be used to describe illumination.

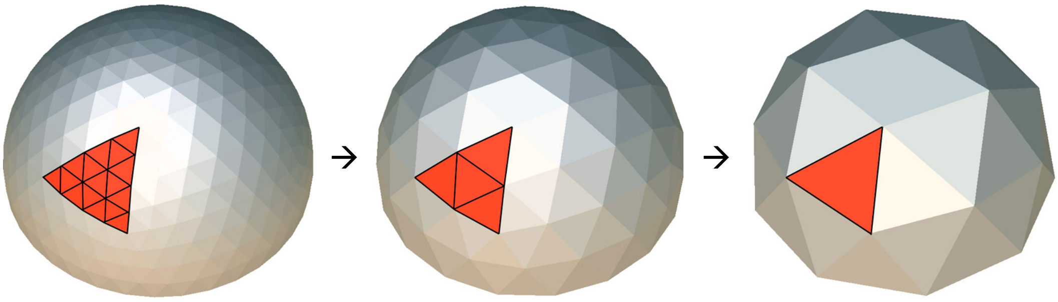

Figure 2: Coherent groups of "skydome" light sources can be grouped hierarchically

GENERATION OF PATCHES

In our approach, the generation of patches from the geometry of the 3D-model is kept relatively simple. Through the definition of a single global size and different local geometric sizes for patches, the entire geometry of the model is subdivided into equilateral triangles. Many approaches use a process of continual refinement of patch size depending upon light exchange with other areas as a means of improving quality in complex areas such as the corners of rooms and edges of areas in direct sunlight or shadow. Other areas in which illumination is more or less uniform are grouped together in large patches. Under constant light conditions this reduces computation requirements. However, in order to be able to respond to changing light conditions, i.e. where illumination is not constant (light can shine almost anywhere into the room), a uniform patch distribution across all surfaces was chosen.

DIRECT ILLUMINATION

For each patch that is illuminated by a light source, a radiosity equation of the form (1) is determined and saved for this patch. In this case the reflectivity ρ_j is chosen to be an independent variable rather than a BRDF, so that an ideal, diffuse reflection of light can be simulated. The radiosity of the light source B_i is also stored as a variable, so that for the initial radiosity computation only the intensive geometry-dependent computation of form factors F_{ij} need be undertaken. As a result a series of equations are stored for each patch which describe their direct illumination. Figure 3 shows a visualization of this computational stage.

LIGHT EXCHANGE

In this stage of computation the reciprocal radiosity between all patches is exchanged. A form of "progressive refinement" according to Cohen et al. (1988) and "hierarchical radiosity" according to Hanrahan et al. (1991) is applied. Those patches receiving the greatest intensity of illumination, i.e. whose number of its direct light sources and sum of calculated form factors is highest, are the first to distribute their radiosity (equations) into the room. In addition, patches can also be agglomerated hierarchically into large patches (of common intensity), again according to a given error tolerance, as a means of reducing the number of form factors that need to be computed. The number of radiosity equations for all patches increases with each new computational iteration by the number of new radiosity equations for all interdependent patches. For each patch, the original illumination equation is multiplied by the form factor F_{ij} and reflection ρ_j in order to determine the radiative intensity (radiosity) of that patch.

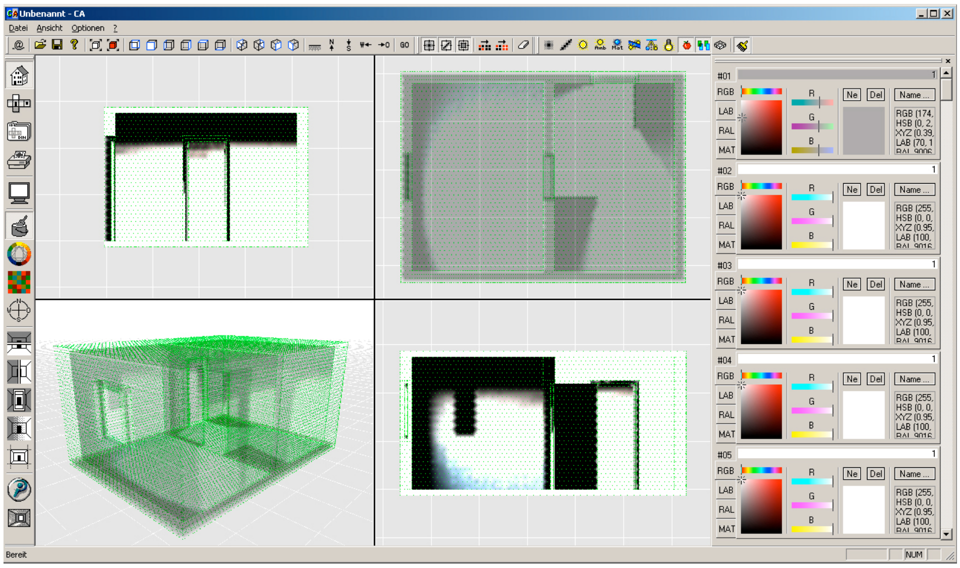

Figure 3: Screenshot from "Colored Architecture" after the direct illumination stage

OPTIMIZATION

The maximum number of radiosity equations per patch is proportional to the number of light sources, the number of radiosity reflections and all visible surfaces in the 3D-model (room) with their own materiality. Through the use of a variable and no angle or wavelength-dependent function for the reflective capacity ρ_j of the materials, it is possible to sum the equations with same variables after each computational iteration. The number of equations can be further reduced through the hierarchy of light sources and error tolerance adjustment. As a result the dependency of the number of equations on the light source can be reduced. Likewise it is also possible to utilize "spherical harmonics" (e.g., Sloan et al.) to optimize the description of the illumination of the patches.

Of particular relevance for the number of equations per patch is the depth of recursion of the radiosity algorithm and the number of different materials present in the room. For architectural visualizations, 3 to 5 reflections of radiosity are usually sufficient and the number of materials used in interiors is usually limited thereby avoiding that the number of equations per patch gets out of hand. The result of the entire computation is a series of radiosity equations per patch that can be solved directly for a particular lighting and material scenario. The sum of the respective patch equations produces the color and luminance of that patch.

The computed radiosity equations are only dependent upon the variables illumination and material properties. In addition, the equations are entirely independent of one another. As a result they can be rapidly computed in parallel for the chosen variables, a task that a graphic card hardware shader can undertake in real time.

USE OF THE BRDF ILLUMINATION MODEL

In the approach described, all surfaces have been assumed to be ideal, diffuse “Lambertian reflectors”. This illumination model is used in many radiosity algorithms such as those used by Cinema4D (Maxon Computer Inc.) and 3D-Studio (Autodesk Inc.). It has limited processing requirements and can be optimized in a number of ways. However, to achieve a more precise and physically-correct visualization of materials, a so-called BRDF illumination model should be employed. The reflective properties of a material, including its color as well as a series of other properties, can be determined from the wavelength of light (e.g. refraction for mother-of-pearl), the angle of incidence and reflection of the ray (reflection), the anisotropy (e.g. brushed steel) and the layers of a material (e.g. varnished wood). These properties are likewise dependent upon the position of the patch in a room and its illumination, so that pre-computed geometry-dependent values and variable parameters can be determined for each equation. As a result radiosity equations can also be developed using this illumination model.

CONCLUSION AND OUTLOOK

It has been demonstrated, that it is possible to develop a fast and interactive radiosity visualization system that takes into account reciprocal material reflections and as such is feasible for use in the design and assessment of color and material concepts. The system can incorporate the physical material parameters of a BRDF model. By optimizing the radiosity computation for fewer design variables, in this case color, material and daylight, a tool has been developed which allows the design and assessment of color and material compositions in an architectural environment. This method contributes significantly to improving the design of surfaces in architectural planning.

Parallel research activities at the Bauhaus-University Weimar are investigating the IT-support of material and product selections in the architectural planning process. Further experimental testing of the “Colored Architecture” software prototype will also be undertaken with a view to developing the software concept further. This includes investigations into the implementation, quality and precision of the digitally designed color and material concepts on site. Efficient digital concepts and planning tools for the design, conception, assessment, realization and evaluation of color and material concepts will be further developed at the Bauhaus-University Weimar. The radiosity concept described in this paper is part of these research activities. The use and validation of BRDF light models is an area with much potential for further research in order to better implement physical material parameters in the design and planning of architecture.

REFERENCES

Bimber, O., Emmerling, A., and Klemmer, T. (2005). "Embedded Entertainment with Smart Projectors." *IEEE Computer*, 56-63, January issue.

Cohen, M. F., Chen, S. E., Wallace, J. R., Greenberg, D. P. (1988). "A progressive refinement approach to fast radiosity image generation." *ACM SIGGRAPH Computer Graphics*, ACM, New York, NY, USA, 22 (4) 75-84.

Dobashi, Y., Kaneda, K., Nakashima, E., Yamashita, H., Nishita, T., Tadamura, K., (1994). "Skylight for Interior Design," *Computer Graphics Forum*, Oslo, Norway, 13 (3) 85-96.

Dobashi, Y., Kaneda, K., Yamashita, H., Nishita, T. (1996). "Method for Calculation of Sky Light Luminance Aiming at an Interactive Architectural Design." *Computer Graphics Forum,* Poitiers, France, 15 (3) 112-118.

Donath, D., Tonn, C. (2004). "How to Design Colour Schemes? Conceptual Tools for the Architectural Design." *Proc. of the 22th eCAADe 2004,* Copenhagen, Denmark, 333-341.

Goral, C., Torrance, K., Greenberg, D., and Battaile, B. (1984). "Modeling the Interaction of Light Between Diffuse Surfaces. " *ACM SIGGRAPH Computer Graphics*, ACM, New York, NY, USA, 18 (3) 213-222.

Hall, R. (1999). "Comparing Spectral Color Computation Methods." *IEEE Computer Graphics and Applications*, 19 (4) 36-45.

Hanrahan, P., Salzman, D., Aupperle, L. (1991). "A rapid hierarchical radiosity algorithm." *ACM SIGGRAPH Computer Graphics*, ACM, New York, NY, USA, 25 (4) 197-206.

Lambert, J. H. (1760). *Photometria Sive de Mensure de Gradibus Luminis, Colorum et Umbrœ*. Eberhard Klett, Augsburg.

Pellacini, F., Vidimče, K., Lefohn, A., Mohr, A., Leone, M., Warren, J. (2005). "Lpics: a hybrid hardware-accelerated relighting engine for computer cinematography." *ACM SIGGRAPH Computer Graphics*, ACM, New York, NY, USA, 24 (3) 464-470.

Richter, K. (2005). *Material Efficiency for Image Output on Colour Printers.* Federal Institute for Materials Research and Testing (BAM). Berlin, Germany.

Schlick, C. (1993). "A Customizable Reflectance Model for Everyday Rendering." *Fourth Eurographics Workshop on Rendering,* Paris, France, 73-83.

Sloan, P.-P., Kautz, J., Snyder, J. (2002). "Precomputed radiance transfer for real-time rendering in dynamic, low-frequency lighting, environments." *ACM SIGGRAPH Computer Graphics*, ACM, New York, NY, USA, 21 (3) 527-536.

Tonn, C. (2005). *Computergestütztes dreidimensionales Farb-, Material- und Lichtentwurfs-werkzeug für die Entwurfsplanung in der Architektur.* Diploma Thesis, Chair for Computer Science in Architecture, Bauhaus-Universität Weimar, D. Donath, 88 pp.

Tonn, C., Donath, D. (2006). *Colored Architecture.* Software Prototype, Chair for Computer Science in Architecture, Bauhaus-Universität Weimar, D. Donath.