BAKING LIGHT: Global Illumination in VR Environments as Architectural Design Tool

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Abstract. As proven in the past, immersive Virtual Environments can be helpful in the process of architectural design (Achten et al., 1999). But still years later, these systems are not common in the architectural design process, neither in architectural education nor in professional work. The reasons might be the high price of CAVEs, the lack of intuitive navigation and design tools in those environments, the absence of useful and easy to handle design workflows, and the quality constraints of real-time display of 3D models.

A great potential for VR in the architectural workflow is the review of design decisions. Display quality, comfortable navigation and realistic illumination are crucial ingredients here. Light is one of the principal elements in architectural design, so design reviews must enable the architect to judge the quality of his design in this respect.

Realistic light simulations, e.g. via radiosity algorithms, are no longer the domain of high-end graphic workstations. Today's off-the-shelf hardware and 3D-software provide the architect with high-quality tools to simulate physically correct light distributions. But the quality and impression of light is hard to judge by looking at still renderings. In collaboration with the Institute of Computer Graphics at our university we have established a series of regular design reviews in their immersive virtual environment.

This paper describes the workflow that has emerged from this collaboration, the tools that were developed and used, and our practical experiences with global-light-simulations. We share results which we think are helpful to others, and we highlight areas where further research is necessary.

1. Introduction

1.1. ARCHITECTURE AND LIGHT

> "*Architecture is the masterly, correct and magnificent play of masses brought together in light.*" (Le Corbusier, 1923)

In the realm of architecture the interplay of light and space has always played an essential part. Many of the greatest buildings fully rely on this combination, as the great buildings of Louis Khan, Le Corbusier or Charles Correa. The complex interference of direct and indirect light, shadows and penumbra was up to now of less importance to the handling of virtual reality in the design process, due to technical limitations or focusing on different themes than the linkage to climatic simulations or the interactive design in VR-Environment (Kieferle Woessner, 2003). Nonetheless today's appearance of VR technology is very technical, stressing the functional parameters of design. This does not meet architectural design practice, which is affected by technical, functional as well as aesthetic questions.

The most famous masters of architecture did not separate design into individual fields, but thought of it as one. Their ability to anticipate the effect of design decisions in the context urban fitting, functionality, construction, concept, interior and exterior spaces and atmospheres mad them superior.

12. ARCHITECTURAL DESIGN AND CAAD

Over the past few years our institute has been laying special emphasis on the research of CAAD-Technologies in preliminary design phases, in order to determine their potentials for architectural design and to work out possible workflows and further developments.

In the professional environment, as the designers of leisure parks are, the presentation of new designs as full textured interactive 3D-models, instead of two dimensional drawings or renderings, proved well in practice (Mine, 2003). The 3D-modelling tools used in this example are much more intuitive than today's CAD Tools. Those 3D-Modelling tools free designers from the limitations given by the usual mostly 2D-based CAD programs. Those most up-to-date modellers enable architects to mould even complex spaces in an intuitive and quick way. Hence most of our students are building 3D-models of their designs during their concept phases. The usage of these models, beyond the creation of still pictures, is crucial in terms of efficiency (Mine, 2003).

Today we experience digital design environments, working with highly abstract CAD-driven methods, tools and display techniques to generate the built environment. The output of this approach can be seen worldwide. It is necessary to enhance the tools used in the design process not solely under the aspects of intuition or power, but in the face of atmosphere, surface feel and the support of a holistic design approach. The integration of light into the first design steps can be seen as a beginning.

1.3. WHY RADIOSITY AND VR? BACKWARDS RAYTRACING AND TEXTUREBAKING?

One of the fundamental steps in every architectural process is the communication and evaluation of the design. CAD techniques served well in this process, as 3D-models of building designs offer completely different ways of presentation and enable viewers to get an instant impression of the future outcome. Although the objectivity of this approach is uncertain, as the (artistic) user of the computer systems has a free hand to manipulate the output in any way he wants—similar to hand drawings and other analogue techniques—the goal of computer graphics to solely produce photorealistic images, can be seen as quite controversial (Green, 1999), the advantage is obvious.

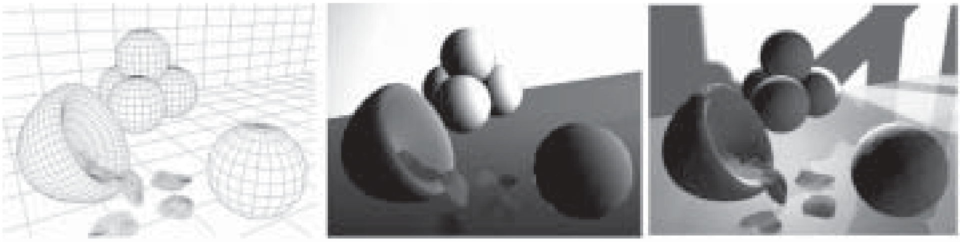
The benefits of CAD-based techniques for architectural work in the realm of preliminary design might be: a consistent workflow, the ability to modify designs more easily than in mockups and the ability to view designs from realistic perspectives and from the interior, enabling the architect to concentrate on parts of the design which are of most importance to later users, as interior spaces. The summit of digital design might be located in an all-immersive virtual design environments, as anticipated in the beginnings of architectural VR (Achten et al., 1999). Yet in our practice CAAD techniques are often outnumbered by simple quickly built mock-ups and their ability to transport abstract information, as structure and texture, at the same time as atmospheric elements, especially real lighting.

In order to understand and evaluate design, the making of three-dimensional models, either digital or as mock-up, is of high importance. As the time needed to build and render digital 3D-models, in comparison to mock-ups, might shrink with enhanced tools and more skilled designers, as seen today, interactive 3D-modelling tools still lack the ability to transport atmospheric light information, as the display technique mostly used is the gouraud shading algorithm. As shown in Figure 1, the atmospheric abilities of other render algorithms are much higher. A design approach taking light even in early design stages into account might offer new possibilities.

14. PRECALCULATED LIGHT VS. DYNAMIC LIGHTING

In order to improve the use of VR in preliminary design, the aim of our work was to transport the virtue of light, as the essence of architecture, with a high amount of light's complexity (different sorts of shadow, reflection and refraction) in an efficient way into virtual environments.

Although interactive raytracers on very expensive high-end parallel machines were introduced in the past (Parker et al.,1999), the rendering time required by these algorithms is still too extensive for interactive applications on standard hardware. Today's 3D-Hardware and 3D-Authoring Tools enable users to interactively change geometry and lighting on desktop systems using directX or openGL Standards or proprietary solutions (e.g. active shade with 3Dmax / discreet (quasi realtime raytracing). Better rendering algorithms will be integrated into desktop systems in the future (Wald et al., 2002; Udeshi and Hansen, 1999), allowing interactive global illumination of 3D-scenes. The improvements in this



(*a*) *Wireframe of the 3D geometry used. 3D-Model provided by MAXON inc.*

(*b*) Viewport of 3D application using gouraud shading and software shaders

(*c*) Rendered image using scanline render engine and 4 point lights to simulate light reflection on walls, etc.

(*d*) *Image using radiosity algorithm and only one light source*

(*e*) *Viewport of scene with baked textures no light source and gouraud shading. A quality close to a rendered image can be achieved in preview mode.*

(*f*) *Rendered image using scanline render engine with applied baked textures. Reflections have not been applied to materials, as they are not compatible with VRML.*

Figure 1. Comparison of shading and render algorithms with representation in 3D-viewport and rendered image.

real can be easily seen on the websites of graphic hardware manufacturers, as nvidia or ati.

Nonetheless neither of these solutions is offering support for 3D-stereo viewing or the parallel display of different view ports on several screens, as used in immersive virtual environments. Thus it might be possible in the near future to view dynamic radiosity on desktop systems, the dynamic display of complex lighting scenarios is unknown within today's VR-technology.

2. From Design to VR

Although the use of dynamic lighting with radiosity algorithms might give enormous benefits to the design phase, we had to concentrate on static light scenes, due to technical restrictions. Nevertheless this made it plausible to use precalculated radiosity solutions, as these are independent of the viewer?s position and direction of view and cover the whole geometry of 3D models. We now just had to concentrate to transport this light solutions into in the DAVE, a five-screen immersive VR-Environment based on standard hardware (Fellner et al., 2003) (see Figure 2).

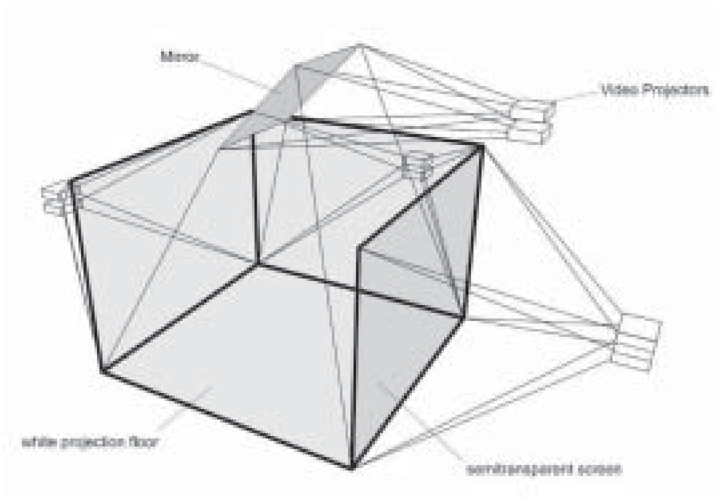


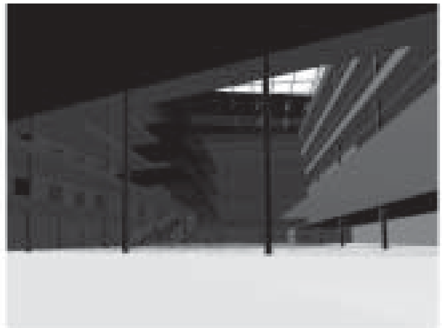
Figure 2. Principle setup of the DAVE at Institute for computer graphics TU Braunschweig / Germany.

The import of 3D-models into this system is done by using the VRML 97 Standard. The DAVE is based on the scenegraph system OpenSG (Reiners et al., 2002) to support multi thread-safe data. The realtime render engine uses a gouraud shading algorithm. A shortly introduced algorithm is providing this setup with collision detection, enhancing the immersion drastically (Fuenfzig, 2002).

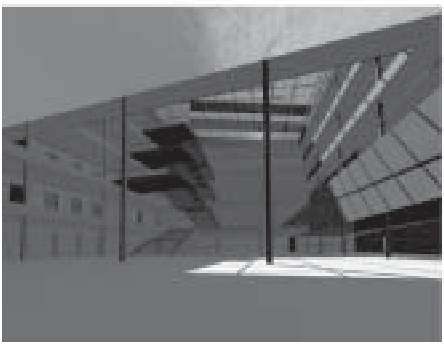
2.1. WORKFLOW (TECHNIQUE)

High-end render algorithms, like radiosity or quasi monte-carlo, (Katz, 2003) are implemented into the 3D-modellers in use by our institute (3Ds-max/discreet and cinema4d/maxon). These high-end render engines are mostly used for rendering stills or seldom animations, due to the high amount of time needed for calculating one picture and the lengthy way to set up correct lighting scenes. Nonetheless advancements in speed and handling of these render engines and contemporary knowledge published in the web, concerning the efficient use of this technique (Mistle, 2004), make it plausible to use Global Illumination in architectural design more often (Figures 2 and 3). In addition, new render engines offer quick previews of radiosity- and caustic calculations, abbreviating the workflow enormously (e.g. vray 1.5 render plugin for 3Dsmax, fprime for Lightwave (Heinzle, 2004).

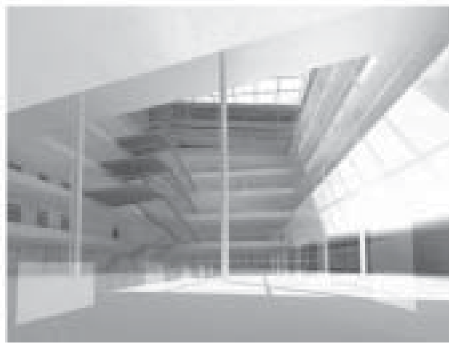
(*a*) Wireframe of 3D-model.



(*b*) Viewport of 3D-modelling Tool using OpenGL display technique.



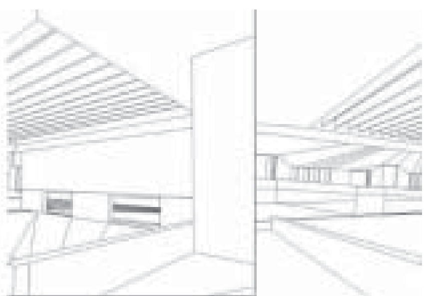
(*c*) Rendering using Raytrace algorithm with hard shadows.



(*d*) Global illumination Rendering using MAXON Cinema 4ds radiosity solution.

Figure 3. Display of an Interior Space (two light sources, 25.000 Polygons, 25 Minutes Rendertime).

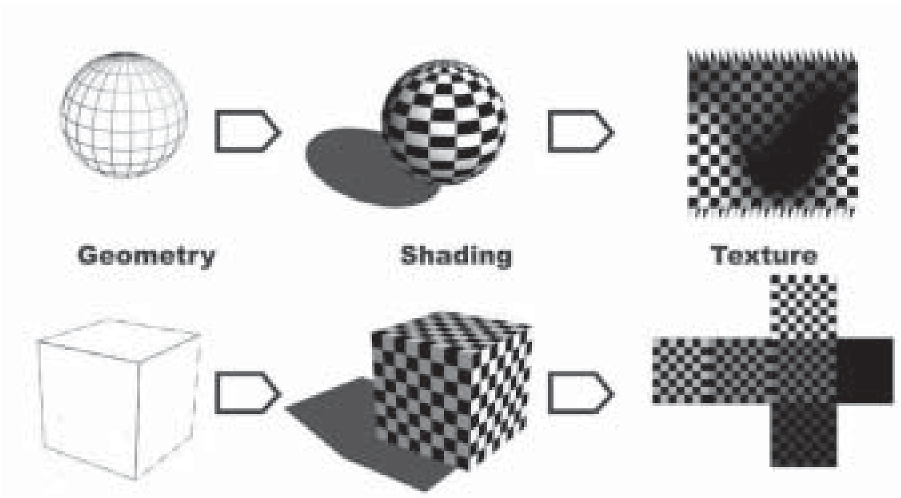
(*a*) 3D model with baked textures. The display of light in the red zones is distracted by artefacts, due to a low number of radiosity sample points.



(*b*) Geometry of 3D-model (1140 polygons) The model was created in a Standard CAD-Software which led to poor segmentation of geometry (triangles). This did affect the radiosity calculation.

Figure 4. Interior scene which has been transported into the DAVE with baked radiosity solution.

The problem with radiosity still is its need for highly divided 3D-models. So adaptive sampling is used to generate radiosity solutions (Cohen et al., 1986), causing high triangle counts, which are still indigestible for today's real-time render engines. Since today's graphic hardware supports realtime texture mapping and Gouraud shading, it was obvious to combine these techniques with radiosity. In 1995 Moeller described a method to transfer the 3D-lighting information of radiosity solutions into UV-textures, which can be easily mapped on objects. This operation, today commonly called texture baking, made its way into some of the current 3D-software. Figure 4 shows two standard primitives in a simple one light source scene and their unwrapped texture with luminance and pattern inscribed (baked). Further advancements and adaptations of texture-based techniques are described (Ray et al., 2003; D´ecoret et al., 2003).



(a) 3D geometry of the sphere.

(*b*) rendered image of the light situation.

(*c*) unwrapped UV-texture of the sphere with texture baked light situation.

Figure 5. Standard primitives in a simple 3D-scene and their unwrapped texture.

2.2. WORKFLOW (DESIGN)

Based on the aforementioned techniques and limitations we established a workflow to transport architectural designs with realistic lighting (Global Illumination-solution) into the DAVE

1. Architectural design using computer based or traditional techniques to obtain concept and basic spatial layout.

2. Creation of 3D-model in a GI compliant way. This means:
3. (i) the use of intuitive polygon modelling techniques and programs (3Dmax, Cinema4d) instead of object oriented ones, as in CAD-software;
   (ii) the use of closed surfaces;
   (iii) polygon reduced modelling technique (Tucker, 2000—Box Modelling).
4. Setting up of materials, lights and atmosphere, usage of realistic light simulation or artistic lighting according to the architectural concept in 3D-Modeller.
5. Precalculation of the GI-solution in 3D-modelling software.
6. Calculation of the UV-textures, using the render-to-texture (discreet 3Dsmax), or bake-texture (maxon cinema4d) functions.
7. Assigning of baked textures to 3D-objects (manually, if not done by the software).
8. Export of VRML97-file.
9. Validation of the 3D-Model and its UVW-texture using the openSG-Viewer (Reiners, 2002).
10. Presentation, evaluation and discussion of the design via vrml-file in small groups (students and Assistant Teachers) in the DAVE.
11. Modification of the design and 3D-model, according to the experiences made in VR.
12. Step 4.

3. Experiencing the workflow

We were surprised at how well the established procedures worked. In comparison to today's common production of textured 3D-models, in an artistic handcraft way, out-of-the-box solutions reduced the time needed drastically. Users, who gained experience in the handling of 3D-models and GI-Rendering before, had little problems in the creation of satisfying VRML-files. Inexperienced users had more problems in setting up the radiosity calculations, than working with the texurebaking procedures.

3.1. BENEFITS FOR DESIGN

The survey of designs in VR-environments can be helpful in order to improve concept, space and detail. According to our focus and the experiences we made, especially interior spaces benefit from this technology. Using VR more frequently might lead to an architectural design focusing more on the interior— the part of a building later inhabitants experience most.

The possibilities to take any point of view in VR-environments, combined with

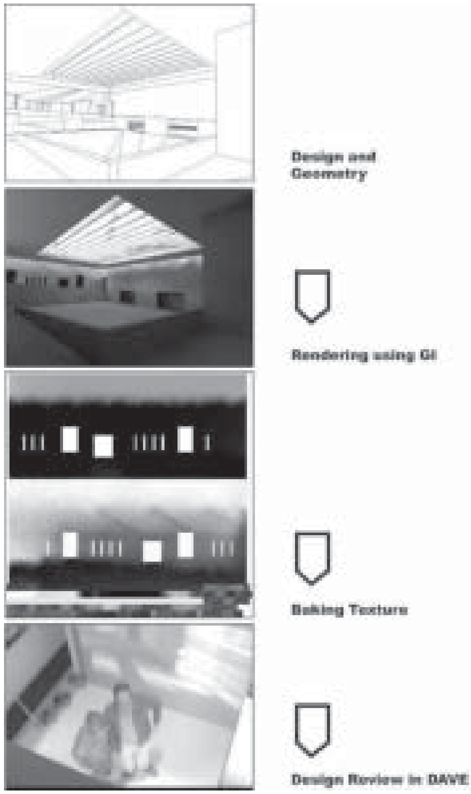


Figure 6. Most important steps during the established workflow.

a close to reality light situation extend the abstract looking display technologies, using Gouraud-shading. As the display quality comes closer towards a normal perception, the degree of immersion rises. Besides the realistic lighting especially the collision detection within the DAVE made the VR-experience more realistic. As flying through walls was prevented, the orientation and control in VR-space was exalted.

Though users of the DAVE can now concentrate more on the architectural design and its problems, immersion is still quite exposing. As the viewer can reach any spot of the design, everything from the overall form to the smallest detail, is unmasked. In early design stages, with limited time and budget, it’s mostly neither possible, nor desired, to make too detailed stipulations. Although this problem exists in any media architecture is presented with; viewers have other expectations concerning Virtual Reality.

As the technique used by us enables architects to get a consistent level of detail with homogenous atmospheric lighting in VR-scenes, attention can be drawn away from irrelevant details towards questions concerning the concept and the designs atmosphere—questions, which are fundamental to architectural design.

3.2. TECHNICAL LIMITATIONS

Although workflow and overall concept worked fine, end-user usability is not reached in the DAVE. The new medium VR is still limited by several constraints:

3.2.1. Clean modelling needed

Modelling for VR-Environments stands for no coplanar planes (z-Buffer-Problems), connected polygons (Box-modelling = easier to texture, better with GI) and the avoidance of holes in 3D-meshes. Disobeying this can induce long render times and deficient display. Although structured working methods are more professional, the compliance with clean modelling standards during the design process might constrict intuition and takes time.

3.2.2. Restrictions due to radiosity algorithms

Today’s hardware and software is hardly able to precalculate radiosity solution for large scale building designs or high detailed 3D-models. Still, smaller or low detailed models work well. Furthermore the scale of the model is important, as generated textures measuring hundreds of metres in the 1:1 scale of the Dave, result in poor presentation quality.

3.2.3. Losses through vrml

As vrml is not a state-of-the-art 3D-format and today’s 3D-modellers support for this format is often step motherly, parameterised objects (subdivision surfaces, Nurbs, etc.) advanced texture technologies (multi-layer-textures, skinning, support of hardware shaders) and the export of animation data is impossible. Figure 7 shows a texture baked for application in a VRML scene. The established workflow using solely core technologies of vrml, without extensions and extra programming via OpenGL or directX technology, does not support dynamic elements, as changing of lights position, colour, etc. or reflections in materials. Taking all of this into account, VRML is outnumbered by most of latter-day 3D-file formats.

3.2.4. Limited Capacity

The limit of 300K vertices in the DAVE, inhibits detailed geometry. So 3D-objects tend to be more abstract, or 3D-information, as ornaments etc., have to be displayed, as 2D-texture.

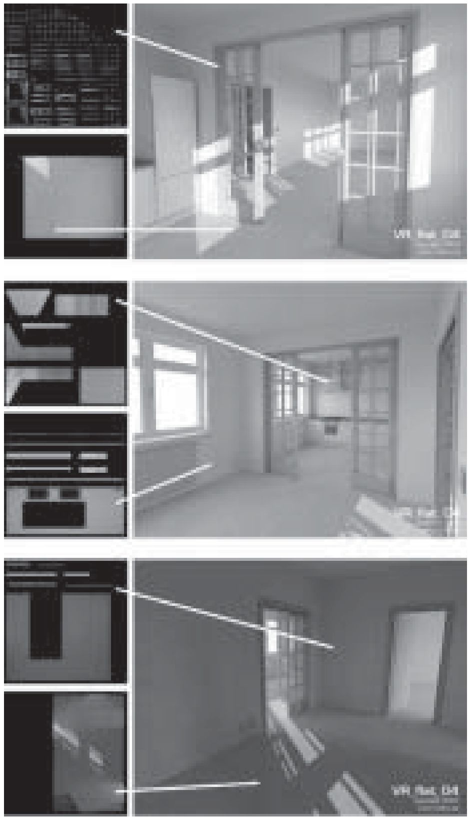


Figure 7. Textures as output of an Texturebaking process and their appereance in the 3D-Viewing Tool (RML file shown by OpenSG Viewer). As VRML doesn?t support lightmaps illumination and information of texture (wood) have to be baked into a single map.

3.2.5. <256MB Textures (unpacked, not jpeg)

Induced by the principle of texturebaking each object has a unique texture, causing a high amount of different textures. In particular large planar areas, as often used in modern architecture, require high amounts of pixels, in order to get a homogenous display quality. As a consequence the graphic memory tends to overflow.

3.2.6. Limited reuse of textures

As a consequence of VRML it is not possible to use tiled textures or 3D-shading tools in combination with low resolution UV-textures, containing the objects illumination information (lightmaps). This technique, implemented in most of today’s real-time render engines, could cut the texture consumption in the DAVE to a great extent, allowing larger models or less time spent in the design phase on optimizing geometry, instead of designing.

3.3. LIMITATIONS DUE TO SOFT FACTORS

3.3.1. Scale

It occurred to us, that users of the DAVE have problems with estimating sizes of objects and areas, although the system is calibrated to a 1:1 scale and the user is using the right position and height of view. The reason for this is implied in the abstract way scenes are normally presented, eluding the user's comparison ro real world experiences. The use of texturebaked quasi light simulations increases the scene's level of detail in a simple way, making it easier to judge the space displayed. Nevertheless the fundamental problem of scale is not solved by this, until elements are placed into the scene or on to the textures, with scales known to the user (ie. furniture, windows, signs, cars or similar details). This was demonstrated in a small but highly detailed interior scene (Figure 6), showing a flat whose proportions ought to be well known to everyone. In combination with a baked radiosity solution an immersive environment was created, where the estimation of scale was no problem.

3.3.2. Motion sickness

Some people experience sickness after a while in the DAVE. The cause is an unrealistically high speed of movement in the VR-environment, which might be thrilling in computer games, but is too high in comparison to a pedestrian's speed of movement.

3.3.3. Problems with orientation

Abstract presentation or the constriction on interiors without reference to the outside, makes orientation in VR-environments difficult. For some part this might be implied in the architectural layout, whose realisation might suffer of the same problems. On the other hand the missing possibility to experience the situation as a whole intensifies this problem. The use of light (sun) and shadow, in the quality presented in this paper, might reduce this hitch, as mankind is used to orientation according to the position of the sun.

3.3.4. Lack of Immersion

The absence of 2 sides in a 4-sided CAVE limits the possible movements. Due to the missing top projection (Figure 7) a crucial lack of information occurs. According to the anatomic position of the eyes and the higher relevance of the ceiling for a spaces impression, crucial information for a correct interpretation is missing.

3.3.5. Tracking

The DAVE system tracks only one person's position and line of sight. We learned that other people understand the display with some experience.

(*a*) View from the top into the DAVE.

(*b*) As the ceiling in the DAVE is missing, the feeling of immersion is constricted.

Figure 8. Presenting the 3D scenery of Figure 6 in the CDAVEC.

4. Future prospects

Until Global Illumination in VR-Environments can be calculated in real-time, render-to-texture algorithms prove well in transporting realistic light situations into the DAVE. Yet too many steps are necessary, until the quality demonstrated is achieved. Besides the reduction of the limitations mentioned above, improvements are necessary regarding usability, necessary steps in software and work process and the knowledge of 3D-real-time-techniques required, to avoid quirks in the process. All this is related to the baking software as well as today's GI-render-engines, which are too complex for everyday use in a design process.

Speaking of immersion means that interaction and intuitive navigation in VR-spaces is of high importance. A natural, smooth and realistic movement is obligatory. Collision detection and a simple dynamic system keeping the virtual character at a natural height and position are simple ways to enhnace the experience in static VR-scenes.

Today's pacemakers in VR-Environments are the Game- and Entertainment industries. Applying their standards to professional VR-systems could keep the VR-systems in use state of the art and help reduce problems with interfaces.

It's possible to raise the understanding of architecture by showing near to life presentations in VR, as shown in this paper. On the other hand, VR-tools which transfer classic-abstract ways of perception in this new medium would be helpful. With a slicing or sectioning tool, for example, one could gain experience of the layout of complex models.

The presentation of "real light", contributes enormously to the appreciation of design concepts in virtual space. Anyhow a realistic lighting simulation is not compulsive, as the artistic and atmospheric value of VR-Spaces in and with relation to reality is yet undiscovered. The position of VR-Environments in the architectural workflow is still not apparent. The amount of work needed today to transport 3D-scenery into VR is still exceedingly high, as to believe VR could already be a standard tool. It could be worthwhile to evaluate the use of better display qualities in VR and its possible significance in the design process. Yet the work undertaken gives a glimpse to the future, where design and simulation tools are joint to give the architect a more intuitive way to design.

5. Acknowledgements

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