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From CAD to virtual reality: modelling approaches, data exchange and interactive 3D building design tools

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Abstract

Virtual reality has the potential to improve visualisation of building design and construction, but its implementation in the industry has yet to reach maturity. Present day translation of building data to virtual reality is often unidirectional and unsatisfactory. Three different approaches to the creation of models are identified and described in this paper. Consideration is given to the potential of both advances in computer-aided design and the emerging standards for data exchange to facilitate an integrated use of virtual reality. Commonalities and differences between computer-aided design and virtual reality packages are reviewed, and trials of current system, are described. The trials have been conducted to explore the technical issues related to the integrated use of CAD and virtual environments within the house building sector of the construction industry and to investigate the practical use of the new technology. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Virtual reality (VR) has been used within the construction industry for design applications, for collaborative visualisation and as a tool to improve construction processes [9], but it is currently implemented in an ad hoc fashion [4]. At Loughborough University, the effective implementation of PC-based VR systems in the industry is being researched. A number of VR systems, including Superscape, VRML and World Tool Kit, have been tested to assess their suitability for integrated use in the house building sector of the construction industry.

VR forms a natural medium for building design as it provides 3D visualization, can be manipulated in real-time and can be used collaboratively to explore different stages of the construction process. In the future, it may be possible to generate and print 2D CAD drawings directly from the VR models that are being used for architectural design. However, in order for the use of VR to mature to such a level, the integration of its use with existing technologies such as CAD needs to become the focus of research [39], and appropriate standards and protocols need to be developed.

Although it is already possible to create VR models from within VR packages, for the use of VR in

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construction industry, the transfer of geometrical data between CAD and VR is desirable to avoid repetitive work [2,10]. The trials undertaken by the authors have posed the question of how to transfer data from traditional CAD systems into VR, and have also assessed the suitability of different approaches to the creation of VR models for different situations.

After a description of the three different modelling approaches identified in the literature, the related technical issues of data exchange, VR systems and 3D graphical standards are explored. The trials of VR systems conducted at Loughborough University are then described.

2. Data translation and practical modelling approaches

2.1. Data translation from CAD to VR

The current process of translation from CAD into VR is normally a one-way or ''downstream'' process (Fig. 1). The CAD model is translated into VR, either directly, or through the intermediate stage of a rendering package. To facilitate the translation process, data on the CAD drawing is often reordered, usually in non-industry standard ways, to control features of the resultant VR model. The user relies on previous experience and prior knowledge of the translator and VR system to create a satisfactory model. Bourdakis [10] notes that there is a trade-off between the amount of time spent reordering the CAD model to suite the translator and the time spent optimising the resultant VR model and ''It is normal to spend a few hours or even days, hand-optimising the translated file'' [11].

Complex and highly detailed CAD data, common in the construction industry, translate into excessively large VR models, but the computational time required to run these must not slow user movement to an unacceptable level. Optimisation to allow real-time viewing is achieved by reducing the information to be processed and hence reducing the computational effort required during each simulation loop.

Three different approaches to the creation of VR models have been identified in commercial applications and VR research projects [39]; these are to build a library of standard parts, to rely on imperfect model conversion through translators, and to use VR as an interface to a central database.

2.2. A library-based approach

A library-based approach, where a library of components is archived for reuse within the VR environment (Fig. 2a), eliminates the need for repetitive data transfer and optimisation of common parts. Significant time and effort is initially required to build up the library, and the library components can be created from CAD data that has been optimised and had behaviours added.

Adeji-Kumi and Retik [1] and Retik [30] have taken this approach for research into the simulation of the construction sequence. As in the work of Op den Bosch and Baker [29], the interest is in the representation of construction activities. Direct translation of a whole model from CAD is inefficient as an item is simply a geometric description in CAD

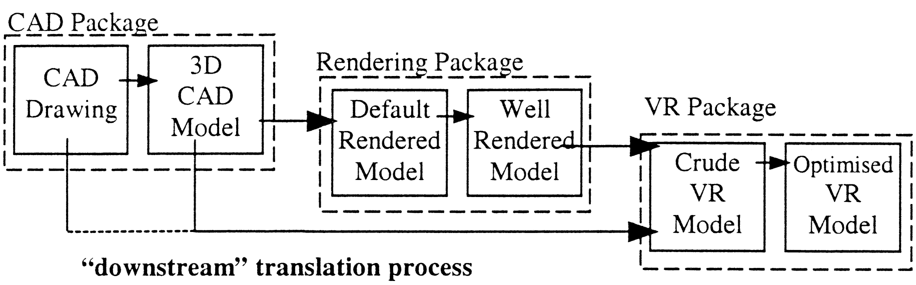

Fig. 1. The current process of translation from CAD to VR is a one-way ''downstream'' process.

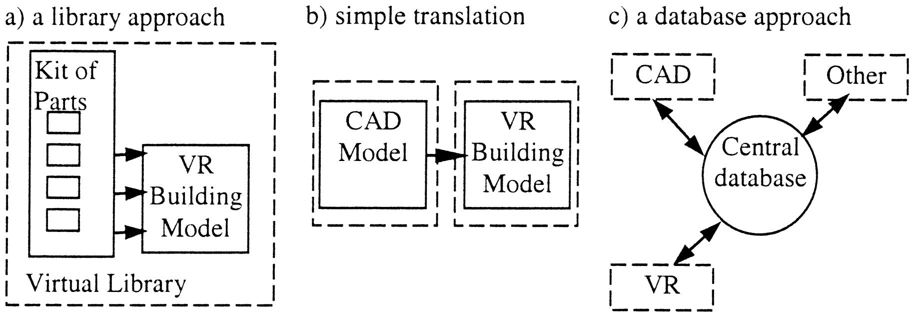

Fig. 2. (a) A library of standard parts, (b) simple translation, and (c) a central database approach.

and does not have associated information relating it to its construction processes. Instead a library of virtual elements is employed [30] to save and reuse information about both the geometrical nature of building components and the related processes. The time taken to create the library is compensated by the reuse of information about the complicated sequences of events.

A library of standard VR components has also been used in a networked system [32] to investigate the potential archival of manufacturers VR models of standard parts. It was proposed that each manufacturer would upload the latest versions of their products and these models could be used directly by building designers in their projects.

2.3. A straightforward translation approach

Complete CAD models can be used to generate VR models by straightforward translation of the whole model, sometimes in conjunction with algorithms for optimisation. A translation approach (Fig. 2b) has been used in research projects where there are few repeated elements, geometric data predominates and there are few activities associated with it, or the design process is completed and the design is fixed and unchanging [39]. Translation and optimisation can be used for the generation of highly rendered or optimised models for presentation to clients.

CAD models of entire cities that were created as student group projects have since been translated into VR urban models at Bath [11,16] and at Strathclyde, although extensive reorganisation and optimisation has been necessary to obtain suitable frame rates in such large VR models.

2.4. A database approach

A database approach to VR model creation utilises a central database to control component characteristics and both CAD and VR are used as graphical interfaces to that database [2,5]. The building model is created in the central database and viewed through the different applications [20], one of which is the VR package (Fig. 2c). A full implementation of such a system would allow updating of the model in both CAD and VR. Thus a two-way data exchange would be effected as opposed to unidirectional or downstream data transfer.

Whilst a database is used for internal organisation and for search and retrieval of information within the urban model of Los Angeles [25], the link between CAD and VR is not dynamic, and there is no central building model that can be viewed in both CAD and VR. Virtual Los Angeles has instead been created by the translation of models created in the MultiGen modeller and using GIS data.

A database approach has not been implemented commercially, but the Open Systems for Construction (OSCON) research project at Salford University uses case studies from real-life construction projects to demonstrate its usefulness [5]. This project, which builds on the earlier ICON project [14], has core modules that include process management, planning, CAD, estimating and VR. Thus, VR operates as the user interface for interrogation of an integrated project database. Whilst the OSCON project could not currently be used for real-time viewing and presentation of large complex building or urban models, it demonstrates the potential of such an approach to VR utilisation.

3. Data exchange issues

3.1. Formats for data exchange

The de facto standards for file transfer between different CAD packages, and between CAD and other design software are the DXF file format, developed by Autodesk, and more recently the native AutoCAD DWG format. Though such standards have often been more successful than the attempts to develop formal standards [35], their proprietary nature has been problematic, leading to incompatibility with different vendors' software, and with different versions.

The development of neutral formats for the exchange of CAD data first started in the 1960s with the Initial Graphics Exchange System (IGES) and out of this research the Standard for Exchange of Product model data (STEP) was developed [8]. STEP is the formal international standard adopted by the International Standards Organisation (ISO) and is concerned with defining product data, some of which is geometry. The pan-industry approach taken in STEP contrasts with the approach taken by a separate initiative, the International Alliance for Interoperability (IAI) to which STEP has made available technologies which support Computer Integrated Construction (CIC) [24].

There is an increasing awareness of the necessity of convincing industry of the business benefits [42] of standardisation initiatives. Founded in 1994 by a group of 12 companies in the US, the IAI is an industry driven standardisation initiative that is developing the Industry Foundation Classes (IFCs). These are a common set of intelligent building design objects that will enable the sharing of information at all stages of the construction process.

There is a need for standards that are straightforward in use and terminology [43]. Standardisation initiatives can become too large and unwieldy to be implemented, or too restrictive. Standard data exchange formats and methods would greatly help the development of protocols for the transfer of construction industry data to VR, but for this the standards would need to support the addition of behavioural information such as the opening and closing of a door.

3.2. Commonalities and differences between CAD and VR

Whilst 3D CAD has evolved from primitive 2D drafting packages that treated lines as simple graphical entities, VR has developed out of advanced work on flight simulators and computer graphics [6]. The construction industry user has not been active in the development of VR, and the computer graphics conventions, used in VR packages, are unfamiliar and often different from established CAD conventions. An example of such a difference is the right-hand coordinate system used in VR, which is different from the established CAD world-base coordinate system. Concepts such as levels of detail (LODs) are also used differently in CAD and VR. Architects have a concept of LOD based on the paper scaled representation of real space (1:5000, 1:1250, 1:500, etc.) rather than the visualisation of varying LODs at the same time. The specification of many values, such as colours and translations numerically (as RGB values, or quaternions), rather than graphically is not familiar to the user of the Windows graphic user interface (GUI) of the modern CAD environment.

Other differences between the packages, such as the hierarchical structure of VR packages, and the lack of a modelling kernel arise from the need to optimise VR models for real-time viewing. Differences such as the use of graphic primitives for modelling and the lack of sophisticated modelling aids such as layers, snap controls, and high precision detailed rulers to ensure the accurate placement of geometry allow for real-time viewing but make VR a less suitable environment for modelling in.

Whilst not themselves truly object oriented, PC based VR systems use a scene graph to organise worlds hierarchically [44]. This is done as trees of different geometries, each of which inherit the translations and orientations of their parents and pass on their own translation and orientation to their children. Such an explicit hierarchical structure is not currently used by the traditional CAD packages widespread in industry, hence the translation of data from CAD to VR formats requires a fundamental restructuring of the data.

There are no standard methods for the translation of building data from CAD into VR. VR packages are generic in nature, and do not offer in-built support for complex domain-specific industrial information. Researchers have developed their own project-specific techniques for the translation of construction data to CAD and the structuring of construction data within VR. As the use of VR for design has not been widely researched, assessment of any particular system difficult [36] and standard methods for the management of architectural data in VR-based design systems have not yet been established.

3.3. Optimisation of translated VR models

Optimisation can be used with any of the modelling approaches described above. Techniques used to optimise models, though commonly used by both game developers and the VR community, are alien to the CAD environment with which the building professional is familiar [39]. Optimisation involves the reduction of the number of polygons to be processed in the VR model and it is done to increase performance, by increasing the frame rate and speed of reaction to user input. This can be achieved by simplifying the model, but such simplifications can be inappropriate and difficult to automate for the representation of building and construction data [22]. Optimisation requires a trade-off between speed on the one hand, and graphics quality and accuracy on the other, and can be achieved using the following techniques.

- The use of primitive solids — simple objects, such as spheres, cubes and cylinders, together with texture maps can simplify the amount of geometric data in a model.
- Distant dependant LODs — simpler geometry can be used to replace complex geometry at a sufficient distance from the viewpoint for the eye not to perceive the loss of detail. Techniques for the substitution of images, or imposters, for distant geometry are also being investigated [17,34].
- Selective loading — visibility sensors determine which part of the model is being viewed and therefore which geometry needs to be loaded and rendered and which behaviour scripts need to be active [31].

The rapid production of VR models of construction projects is hampered by the lack of standard protocols for the translation of data from CAD and the optimisation of the VR model. The unidirectional nature of the data flow from CAD to VR and the time taken for data translation and optimisation limit the effective utilisation of VR in the iterative design and construction process.

3.4. Interactive 3D building design tools of the future

Future CAD systems may use standard methods for describing building data, be semantically richer and based on the object-oriented paradigm. They could be based around intelligent building design objects that encapsulate both data structures and methods [18] and inherit properties from more generic objects.

Advanced 3D visualisation techniques, such as wireframe, solid modelling and quicktime VR are available in many contemporary CAD packages, as is the ability to export to 3D formats such as VRML.

Some VR capabilities are likely to be incorporated in the next generation of CAD tools. The 3D model may be used in the design process, with 2D views and sections being generated dynamically from it using sectioning tools. An early design package Sculptor [21], has been developed in which the architectural design is supported in the VR environment. Research is also ongoing into tools that simulate the construction process [26] within the CAD environment, using the spatial dimensions *XYZ* and time.

Thus many VR techniques can be incorporated into future building design tools for rapid prototyping of design, and the simulation of construction processes. VR packages will continue to be used within the AEC industries, when optimisation techniques are required to attain high frame rates, or when support is required for hardware devices.

4. VR systems and 3D graphics standards

VR systems range from a simple set up on a desktop PC, to high-end VR labs using silicon graphics (SGI) computers with additional hardware for stereoscopic vision and auditory and haptic feedback. Whilst the computational power available has an impact on the potential for achieving real-time viewing of complex data sets, the principles of modelling, described in Section 3, are the same in both low level and high level systems.

4.1. 3D APIs — Open GL and Direct 3D

VR packages are built on graphic Application Programming Interfaces (APIs) that provide low-level procedural models for 3D graphics.

At present many VR systems are built on the Open Graphics Library (Open GL) or Microsoft's Direct 3D. Open GL is a non-proprietary standard API, the creation of which was initiated by SGI in 1992. Unlike Direct 3D, which is limited to the PC platform, it is cross platform, and has been important in the development of many high-end and commercial VR systems. Such a low level API offers a way to render a simple set of graphics primitives such as points, lines and polygons, but further APIs are needed to build on this and offer a greater level of abstraction, and scene management functionality. SGI's Iris Performer and Open Inventor APIs build on Open GL, and are often used to provide further functionality allowing the programmer to concentrate on world creation. They have been utilised directly, as well as indirectly, in building research. Iris Performer was designed for high-end visual simulation on SGI computers and can support fixed frame rates. It has been used for interactive visualisation of large architectural models [22,25]. Open Inventor was designed to be more general purpose than Iris Performer and is portable to non-SGI systems. It has been used in building research projects, for direct manipulation of designs within virtual environments [41], and for design review [27].

4.2. VRML and 3D web technologies

Virtual Reality Modelling Language (VRML), which in its first version was based on a subset of Open Inventor, is now the international standard for 3D modelling (VRML'97 — ISO/IEC 14772) [37]. CAD packages, modelling applications, and proprietary VR applications export directly to it, and VRML models can be viewed, either locally or distributed across the Internet, through a plug-in in a web browser such as Netscape or Internet Explorer.

Building research projects using VRML include libraries of product data information [28], the VR interface to an integrated project database [5], and large-scale urban models [10,15] as well as a multiuser design environment [27].

4.3. Proprietary PC-based VR systems

As well as the standard for 3D modelling, VRML, there are many commercial PC based VR packages which contain in-built modelling environments for world creation, and libraries of routines for the addition of behaviours. They are based on APIs such as Open GL, and Direct 3D but offer some higher level abstraction. Among the leading commercial VR packages now available on the PC are Superscape, WTK and Division.

Superscape is one of the early PC based VR packages (originally running in DOS on a 386 processor) and in the version used (VRT 4.0) in this research, it was found to be difficult to import large-scale 3D models from CAD into Superscape. Building research which uses the Superscape software includes construction scheduling in which a library of standard parts are built up within the VR environment [30].

WTK is a set of C functions with which customised VR applications can be written. Applications written with WTK can read AutoCAD's dxf files, 3DStudio's 3ds and VRML wrl files directly, as well as reading and writing to WTK's own native ASCII text based format, called neutral file format nff. It has been used for building research by the Japanese company, Matsushita Electric Works, in their Kitchen Planning Support System (KiPs) [33], by the VR-DIS design application developed at Eindhoven University [12] and in the ICON integrated building database project [3].

One of the advantages of such a system is that software development and VR model creation can be separated into distinct activities, undertaken by separate specialists, and that the software can be highly customised to the specific task required by the construction industry user.

The Division package is a family of product simulation tools. It is one of the early VR packages and, though it was not originally developed on the PC platform, it has also been used in building research projects and for engineering applications [18].

5. Trials of current VR systems

Trials were conducted to investigate the practical modelling approaches discussed above and further explore some of the technical issues.

5.1. Specific modelling requirements

The work is focused on the implementation of VR in the house building industry. Before the trials commenced, an in-depth interview was conducted with a housing developer to determine the nature of the house building process and the requirements for the VR model. Discussion established that house types were designed in the central office, and then sent to the regional offices where they were used on site layouts. The house building industry is standardised to an extent common in the manufacturing industries [23], and the number of standard house types used by any particular housing developer is relatively low. Unlike the rest of the AEC industry, house building is not concerned with one-off construction but has a semi-standardised and repeatable end product.

Work was undertaken to trial different modelling approaches and VR systems for their suitability in house building. The investigation of appropriate methods for an integrated use of VR as a design tool within the house building process benefited from the input from various regional and national housing developers who commented on the different models created.

5.2. Hardware and software used

This research was undertaken using computers similar to those found in industry today rather than a highly specialised academic VR research laboratory. The computers used are a 32 Mb RAM 133 MHz Pentium PC with a 4 Mb Matrox Millennium graphics card and a 128 Mb RAM 300 MHz Pentium II Pc with a 8 Mb VRAM/32 Mb DRAM Diamond Fire GL 3000 graphics card, and a 6 degrees of freedom Magellan Space Mouse.

Industry standard design tools such as AutoCAD and 3D Studio VIZ were used for model creation, and the PC based VR Systems used in the trials were VRML, Superscape and World Tool Kit. CosmoPlayer was the browser plug-in used to view the VRML models, in both the Netscape and Internet Explorer browsers, and VRealm Builder and Notepad were used to assemble and edit VRML models.

6. Models created in the trials

6.1. Library of standard house types for site layout appraisal

In the first VR trial [39,40], using the Superscape VR system, a library-based approach was taken toward modelling. After consultation with a leading UK housing developer, it was agreed that a library of house types, with their associated LODs and optimisations could be built up in VR.

The rationale behind the use of this approach was that, in a practical setting, a library of house type models could be built in the central office and sent out to the regions. In the regions this library could then be used for the rapid generation of detailed site layouts.

In the trial, 2D AutoCAD data was obtained from the housing developer. Attempts to build a 3D model in AutoCAD and then transfer this to Superscape met with only limited success. As the 3D data transfer was unsatisfactory, the 2D plan data was transferred to Superscape, and the 3D virtual model was assembled inside the package from the 2D AutoCAD data and the parts of 3D model successfully transferred. It was found that the translator was inaccurate and dimensions of the resultant model had to be checked.

The final model created was highly detailed and then it was instanced and simplified to create two other LODs. These could be substituted for the detailed model when the house type was at such a distance that the eye could not see the detail. Thus a sophisticated virtual model of a standard house type was created in VR from AutoCAD data.

This model of a standard house type was placed in different locations in a housing layout (Fig. 3) to demonstrate the potential use of a library of house types.

In this trial it was found that the data transfer between CAD and the VR package used was extremely cumbersome. The creation of the VR models

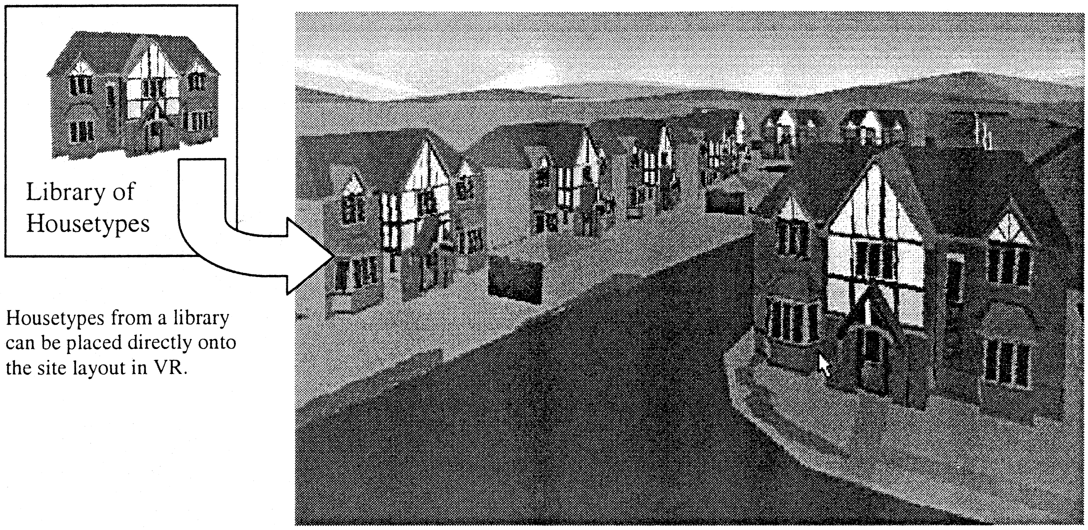

Fig. 3. A site layout showing the use of a standard house type to rapidly generate site layout models from a library of VR models, in Superscape.

of the standard house types was time consuming. Although the library approach eliminates repetitive data transfer by reducing the amount of translation required, this early work led to the consideration of the potential of standard 3D formats such as VRML and the possible development of standards and protocols for data transfer to them.

6.2. Library of standard house type in VRML

Building on experience gained in the first trial, the second model also used the library based approach to model creation, but was built from CAD data of the house type that was translated into the VRML and assembled in an authoring tool (Fig. 4). First 3D models of the house types were created in CAD. These were taken into 3D Studio VIZ and then translated into VRML, using the in-built translator in the 3D Studio VIZ package. The site layout data, which in this trial was 2d, was also translated from CAD to VRML, via the in-built translator in the 3D Studio VIZ package.

The facilities for data transfer were much better but VRML was not very efficient at supporting complex geometry at near real-time speeds.

Using a VRML authoring tool, VRBuilder, the house type models could be duplicated and placed onto the site model. Various different house type models were produced, but difficulty was experienced with the accurate placement and movement of different models in the VRML world.

The VRML standard format was used for this model so that it can be accessed from any computer with a VRML browser plug-in installed. After viewing the model in the CosmoPlayer browser plug-in, some changes were made to the VRML code in Notepad. An applet was used to give the current

Fig. 4. House types were placed into VRML and hyperlinks to other information was added.

coordinates of the viewpoint, and this was found to be of great use for the setting up of Cameras etc, but the VR environment was view only, and had insufficient support for sophisticated interactive manipulation of the data.

This model does however demonstrate the potential for VR models to be accessed through a browser, either remotely, or on the local computer. Technical data or photographic marketing images can be displayed when the user enquires about relevant parts of the housing scheme from within the virtual environment using hotspots. In this trial, this was achieved by creating HTML pages, to display the model in a HTML frame; and editing the VRML code, to add hyperlinks from the VRML house type models to further information which would display in another frame of the browser.

6.3. Straight-forward translation from CAD into VRML

In a further trial, a 3D model of a housing development was created in VRML [38,40], and then displayed in a web browser (Fig. 5). This was undertaken to further demonstrate the potential of 3D web technologies, such as VRML, to housing developers and other construction professionals. Because of the difficulty experienced in assembling models in VRML, and the need to create the model rapidly, a straightforward translation approach was taken with a simplified model. The model was built in 3D in the AutoCAD environment and then exported to 3D Studio VIZ, where it was structured hierarchically and further edited before being translated into VRML. The VRML site model is not as refined as the initial house type models. It is a massing model, which just shows the general layout of the site.

House types were not modelled in detail, and a library of house types was not used, as excess detail would increase difficulties of bandwidth and hinder the attainment of real-time viewing.

6.4. Standard house types in a site layout

In the creation of later models the World Tool Kit software has been used (Fig. 6), and modelling approaches have been chosen to suit the different modelling tasks within the model. Housing layouts have been created by the substitution of detailed house type models, from a library of house types, into a simple model of the site that had been translated and filtered. As WTK can import models in VRML,

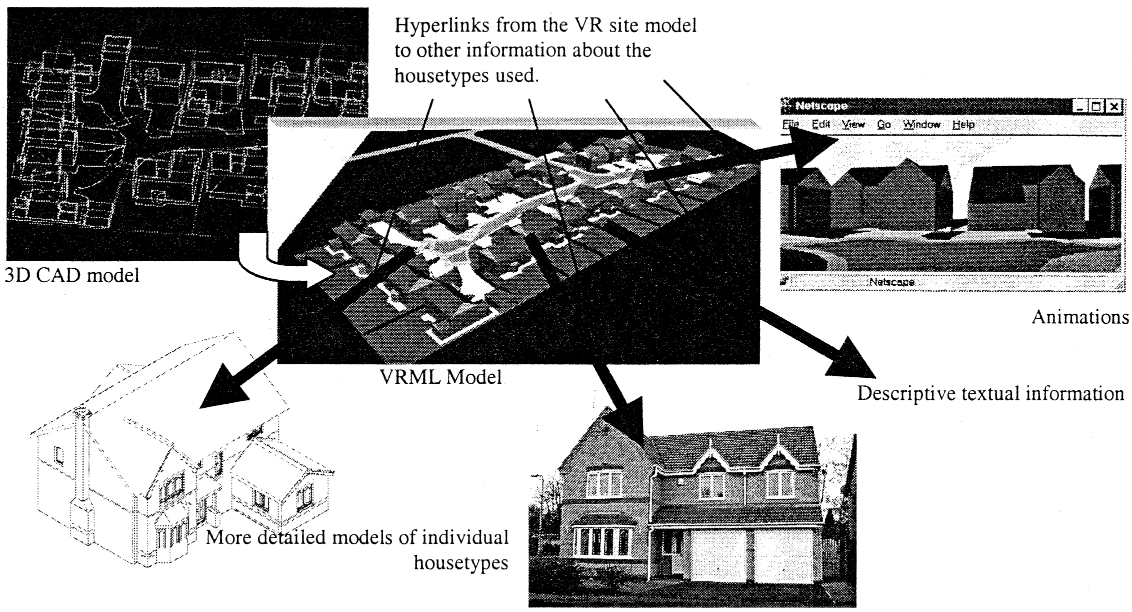

Fig. 5. The 3D CAD model was translated into VRML and then hyperlinks to technical and marketing information were added.

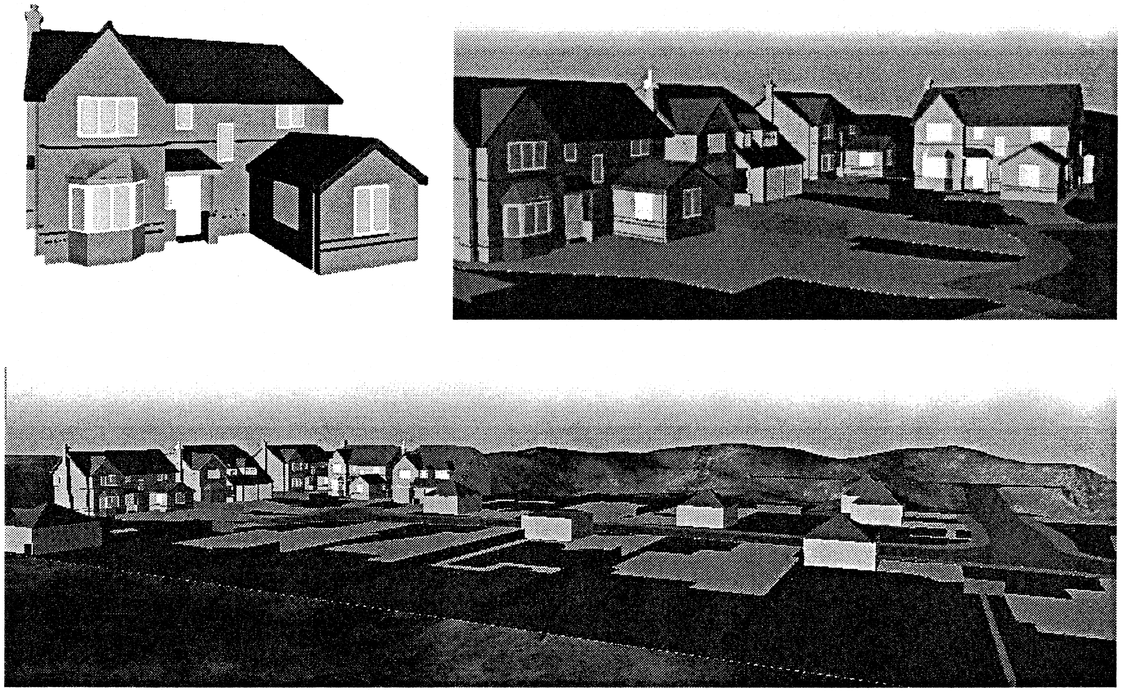

Fig. 6. 3D Studio models were created from 3D CAD models and were viewed in WTK, where they were positioned on the VRML site layout.

DXF and 3DS file formats, as well as well as the native NFF, modelling work undertaken for previous models has been reused. The simplified VRML model described in Section 6.3 has been taken into the WTK and then the 3D Studio models of house types described in Section 6.2 have been added to the model. The advantages of the library approach and the straightforward translation approach are combined.

7. Discussion of the different approaches

The library-based approach was found to be particularly suitable for this application of VR. Rapid generation of VR models is needed for the evaluation of site layout by housing developers during the design stage. The translation of all the house types with every site model would involve significant repetitive work and would increase the time required to produce the VR models. Archiving VR models of the standard house types allows users to rapidly generate detailed site layout models for use in discussions within the company and for presentation in planning proposals, without the need for repeated data translation. Additional information about standard house types, such as technical data or photographic marketing images, can be added to the VR models of standard house types in the library. This information can then be displayed when the user enquires about particular houses from within the virtual model of a specific housing development. A library of house types could be maintained by the central office of a housing developer and sent out to the regional offices for use in site layout design.

Straightforward translation was appropriate for the creation of a single model, for display over the Internet, or at the marketing stage, when the site layout design is fixed. For the use of VR during design and evaluation of housing developments, site data could be transferred from CAD to VR on a one-off basis and then the library-based approach could be used to add more detailed 3D models of standard house types.

A database approach would allow changes in VR to be seen in CAD, but would need to be sophisticated to allow the required optimisations and LODs to be associated with individual house types. The implementation of the database approach would require the creation of a central database for the building model using a neutral format accessible by both CAD and VR systems. This concept has been demonstrated through projects such as ATLAS [6], CIMsteel [12] and OSCON [5], however development of such scale is beyond the scope of the work presented in this paper. On the other hand, the models based on this concept required by software implementers in order to develop the software which would facilitate the process are not yet available.

8. Conclusions

Construction industry professionals, though potential users of advanced 3D technologies, have had little impact on the development of VR technology. This evolved from concepts laid out by computer graphics programmers developing flight simulators and military applications where the attainment of realistic real-time interaction is critical. Optimisation of VR models, through the use of primitive solids, distant dependant LODs, and selective loading, shows their concern with navigation of realistic environments rather than the accurate but interactive portrayal of geometric and architectural information.

Toolkits for the creation of VR environments, such as SGI's Iris Performer and Open Inventor, have been important in the development of VR, and have been used in building research projects. A subset of Open Inventor formed the basis for the first version of the Virtual Reality Modelling Language (VRML 1.0). This was designed as a file format for the interactive exploration of 3D models on the Internet and has now become the formal ISO standard for 3D modelling (VRML'97). VRML has made VR techniques more widely available, thus impacting low end PC-based VR, modelling and CAD packages, which now export to this format.

Whilst many VR techniques can be incorporated into future building design tools for rapid prototyping of design, VR packages will continue to be used within the AEC industries, when optimisation techniques are required to attain high frame rates, or to provide support for hardware devices.

VR is currently used in the construction industry and building related research for design applications, collaborative visualisation and as a tool to improve construction processes. In the future the use of VR techniques will mature, as some techniques are incorporated into interactive 3D building design tools. The translation of building data to specialist VR packages will be facilitated by the increased similarity in the structure of the packages and the adoption of formal standards for data organisation such as IFCs and 3D formats such as VRML.

Three different practical modelling approaches for VR applications have been reviewed as part of the work presented in this paper; the library-based, straightforward translation and database approaches. These were explored within the context of house building highlighting the potential use of the new technologies in different practical situations within this sector of the industry. It was found that different modelling approaches were more appropriate for different tasks.

- A library-based approach is useful when straightforward data transfer is cumbersome, when complicated activities or extensive attributes are associated with the sets of geometric data, and when standard parts are frequently used.
- A straightforward translation approach is more suitable when geometric data predominates and there are few activities associated with the data. It can also be used when the design process is completed and the design is fixed and unchanging.
- A database approach can be used for rapid prototyping, where a central database controls component characteristics and both CAD and VR are used as graphical interfaces to that database.

These trials show the potential of PC-based VR systems to facilitate visualisation of building models.

The use of library-based approach was time consuming at the outset but offered the possibility of rapidly producing models with a high level of detail. This also demonstrated that such a system could be used by housing developers to produce alternative housing layouts for discussions within the company and for presentation in planning proposals.

A straight translation offered a faster option for producing the initial VR site layout model and could be used for the creation of a single VR model.

A database approach to VR model creation, though not commercially available today, may arise out of developments within the CAD and VR communities.

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