VISUALISATION IN BUILDING DESIGN AND ANALYSIS

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ABSTRACT: Research on data visualisation is undergoing major developments in a number of different fields. These developments include investigating ways of applying visualisation techniques and systems for more efficient manipulation, interpretation and presentation of data. In the built environment field, the potential of new visualisation technologies to enhance the presentation of performance data obtained as output from simulation programmes (of the type used by engineering design consultants, for example) has remained almost unexplored. Improvements in this area would lead to a better and more efficient use of these simulation programs and would facilitate the interpretation of such output data by construction industry professionals, leading to better, more informed design decisions.

The primary aim of the work summarised here was to commence the development of a method for visualising the data produced by thermal analysis tools; the method should ultimately be operable on an average desktop PC, should be easy to maintain/customise and, above all, should be able to present the data in an intuitive manner.

Two applications were therefore proposed in the study presented here. The first is designed to automatically process the output within a commercial spreadsheet. The second is designed to display the solution in three dimensions to aid spatial recognition and data navigation.

This study shows, through small-scale user tests, that each of the proposed applications significantly improves some of the attributes associated with usability, namely; learnability, efficiency, memorability, errors and satisfaction. Advice is given on the key aspects that require attention when the full method is developed.

Finally, it should be possible to develop low cost data visualisation tools to improve the overall usability of a thermal analysis tool within a built environment practice.

KEYWORDS: Visualisation, Data, Thermal Analysis, Building Performance, VRML, HTML

1. INTRODUCTION

It is recognised that, given the complexity and diversity of the modern non-domestic building, the level of realised performance (in the indoor environment) is increasingly dependent upon the level of integration in the design process (Shaw, 1996). As a result of this, and the rapid increase in computational power available, thermal analysis tools are becoming more comprehensive and their results more extensive and complex. The traditional methods of presenting the output data are rapidly becoming insufficient as a means for clear communication and alternatives must be sought.

This paper presents an initial study of scientific data visualisation and its effective use in the thermal analysis of buildings. Visualisation in this context is focused on the analysis and exploration of data to gain greater insight, and falls into two broad categories (Larkin, 1997):

- Visualisation, where the user is looking to understand the problem;
- Presentation, where the user is presenting results to a third party.

The objective of this work is to aid the engineer in understanding the predicted response of the building to external (weather) and internal (heat gain) stimuli and the effects of design options on this response. Further work will seek to develop tools for presenting the knowledge gained during analysis to fellow engineers, architects and clients.

2. PRESENT RESEARCH

Data visualisation has undergone major developments in the last decade resulting in systems and tools which have become mature for producing visualisation applications in areas such as Computational Fluid Dynamics (CFD), Medicine, Social Sciences and the Environment (Cox 1992, Chen 1993, Kim 1995 and Post 1995). A comprehensive review of these systems is presented in the AGOCG Technical Report 9 (Brodlie, 1995).

It is being demonstrated that further system enhancement can be achieved by coupling together visualisation systems and Virtual Reality (VR) systems (Wood 1996 and Sastry 1998). However, in the construction industry, the use of VR has focused on the visualisation of existing or newly designed buildings, construction sites and interior layouts (Counsell 1997, Hosein 1997, Griffin 1995 and Penn 1995). Further work has focused on combining the imagery generated for these applications with the real world in the form of augmented reality, (O'Connor, 1998).

Schmitt (1993), on the subject of Virtual Analysis, states that VR facilitates analysis in that it lets the designer experience simultaneous views of a building and related analysis data. He summarises that virtual analysis is an appropriate tool for confirming or refuting design theories, be they of geometric, acoustic, energy, or of any other quantitative and computable nature. However, to date, very little work has been done to explore the use of visualisation or virtual technologies to represent building performance data.

The following section details the results of an initial literature survey. The authors would be pleased to receive any further references that may be applicable to this area of study.

2.1 Building Performance Visualisation

In a recent report (CIB TG24) on the use of VR in the construction industry the section on building performance (3.3.2) discusses the role of VR as an integral component of a performance toolkit. As the definition of VR becomes ever more blurred its boundaries open to include desktop 3D graphics and technologies such as VRML (Virtual Reality Modelling Language) making 'VR' more accessible to the construction industry. Example projects include OSCON (Open Systems for CONstruction), which uses a VRML interface integrated with an object-orientated database to support construction processes (Aouad, 1999). More specifically tailored to building performance is a group project reported by Malkawi (1997) which developed a single room model (in VRML) to visualise the effects of a wall's construction on space conditions. The virtual world allows a user to test various combinations of building components (wall material, window size etc) and to visualise thermal distributions while experiencing an interior space. This system is reportedly limited to the pre-calculated results and construction elements.

Another important issue is information management within both building design and VR tools. Whyte (1999) argues that data transfer between the two is neither reliable nor desirable; instead VR techniques need to become accessible within the specialist building design tools. However, care should be taken when combining systems, as the complexity of modelling real world systems in 3D/CAD packages could result in very inaccurate results (Whyte, 1997). Engeli (1996) has demonstrated one such successful combination in his paper 'Virtual Reality Design Environment with Intelligent Objects and Autonomous Agents'; here, the author describes the agents as enhancing the support of the user by solving specified tasks. Although the agents employed are tailored to architectural design, they could be extended to become energy or performance agents. The current literature details many efforts to combine VR techniques with building design, examples are:

- Sketch design stage - 'Pangea' (URL 1)
- Architecture and urban planning - 'VR-DIS' (Coomans, 1999)

- Detailed airflow ‘Phoenics VR’ (Bertol, 1997)

Although there is much to learn from each of these, there remains no definitive technique for representing building performance data to support the detailed analysis of design options.

3. BENEFITS

The benefits to be gained from appropriate use of visualisation should not be underestimated. The benefits are as follows:

- Effective simulation: by supporting cognition, visualisation improves the accuracy and completeness with which users achieve the specified goals. Card (1999) states that there are six major ways in which visualisations amplify cognition: (1) by increasing memory and processing resources available to the users, (2) by reducing the search for information, (3) by using visual representations to enhance the detection of patterns, (4) by enabling perceptual inference operations, (5) by using perceptual attention mechanisms for monitoring, and (6) by encoding information in a manipulable medium.
- Efficient simulation: visualisation can reduce the resources expended in relation to the effectiveness by which the specified goals are achieved. Schulz (1998) note that in the BMW motor company, approximately 60% of effort involved in a typical simulation goes into the analysis and communication of the results and cite this as a strong incentive to produce powerful and intuitive visualisation tools.
- Increased Simulation: the effect of the above is to promote the use of simulation in the construction industry. Simulation assists the developer, the architect and the HVAC designer when they compare design alternatives and choose between them, as well as the designers to select and dimension technical systems (Markku, 1998).

4. CURRENT PRACTICE

The first stage of the study reported here was to identify current practice in the use of simulation within a large civil engineering company. In addition to the feedback received in the day-to-day support (by the principal author) of the analysis software, a workplace observational study was conducted. In this context, the ‘observations’ consisted of monitoring engineers using thermal analysis software in the course of their normal work and recording key tasks. This revealed that each engineer was spending a significant amount of time searching, formatting and manipulating the output within commercial spreadsheet packages. The following critical tasks were identified as being the most significant:

- Inspection of predicted internal temperatures and the monitoring of peak conditions.
- Location of glazed elements transmitting significant solar radiation.
- Identification of high internal surface temperatures.
- Monitoring the effect of the size of ventilation apertures on the internal conditions and space air change rate.

In addition to which it was often necessary to answer such questions as:

- Why is room/surface ‘x’ so hot/cold?
- Why does so much of the transmitted solar radiation pass back out of window ‘x’?
- Which window should have additional blinds/shades added?
- What is the floor area?

Some of the above questions may require collaboration between colleagues to obtain the correct answer, at present, this means e-mail, phone and personal meetings to discuss the problem. Aouad (1999) states that traditional computational techniques have failed the construction industry due to the amount and complexity of the information to be processed.

He goes on to report that modern visual technologies can resolve many of these issues by providing three-dimensional interfaces that allow construction professionals to use the visual model as the medium for communication, interaction and interrogation. The following section details the requirements set for a prototype system to achieve this goal.

5. SYSTEM REQUIREMENTS

Here we describe the criteria set for a prototype visualisation system. The basis for which are the constraints found within an everyday working environment of an engineering practice and the quantity/format of the data to be presented.

5.1 Data Capacity & Structure

In contrast to the other industries mentioned earlier, the data sets used within the built environment are relatively small, but are often complex in nature. They are typically of a relational or object orientated structure and may contain time dependent values. They are however not volumetric. For example, the thermal analysis of an extremely large tropical plant exhibition space located in the South West of England consisted of just over 60 surfaces (*Figure 1.*); in contrast, the CFD model of the same space consisted of nearly 500,000 finite volume cells.

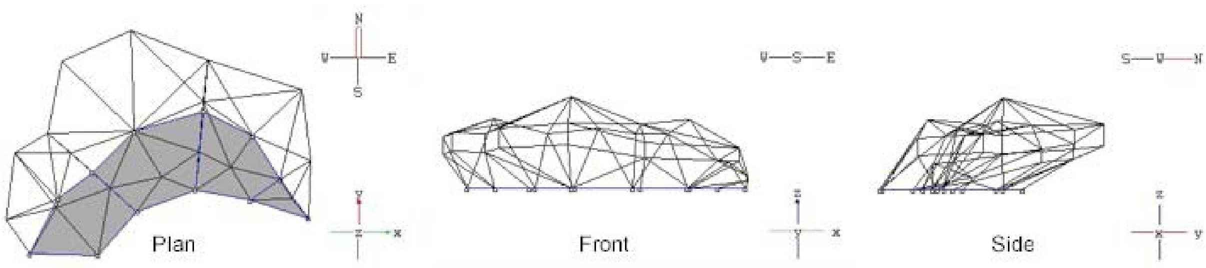

Figure 1. Thermal analysis model consisting of 60 surfaces

CFD results consist typically of values of temperature, velocity and moisture content for each cell in a relatively simple data structure. The thermal results consist of data on many different levels of detail (site → building→ room → surface → fabric) and for various time periods (year → month → day → hour and sub-hour time steps). Therefore the prototype system should be capable of displaying different levels of detail at different time steps, as opposed to large volumes of data for a single (or limited) time-step.

5.2 Cost

Many of the visualisation systems currently on the market are seen as prohibitively expensive in relation to typical project fees. There is, however, presently a surge in the number of low cost technologies capable of displaying the quantity and type of data required - these range from 3D file formats to graphics libraries:

- VRML2 –an international standard for 3D modelling (ISO/IEC 14772)
- VTK – The Visualization ToolKit (VTK), is an open source, freely available software system for 3D computer graphics, image processing, and visualisation.
- OpenGL – an advanced 3D graphics Application Programming Interface (API)

These, when combined with the power of visual programming interfaces such as Microsoft’s Visual Basic, have the power to produce effective visualisations for at least small datasets, allowing rapid proof of concept. Further work will ultimately consider more sophisticated systems for the added usability and functionality they may offer.

5.3 Hardware Platform

To be effective in the workplace the system must not require computational power in excess of the average CAD specified PC, even lower in some cases. This constraint is due to the nature of the environment in which the visualisation must be undertaken, i.e. the everyday working environment of a civil engineering practice. These practices are typically running desktop PCs with the Windows NT operating system and have only limited access to high-end machines. It would also be advantageous if the system was capable of producing visualisations that could be published online, thus supporting collaborative viewing between various parties.

5.4 Data Format

The system's underlying data structure should be defined in line with present standards to allow data transfer between the analysis tools and the visualisation application. There are many existing standards, each with a particular focus:

- STEP – Standard for the Exchange of Product model data (ISO 1993) is a computer sensible data transfer standard which supports design, reuse, and data retention, and provides access to data across a product's entire life cycle.
- IAI – International Alliance of Interoperability (URL 2) the aim of which was to produce standard data modules known as Industry Foundation Classes (IFCs).
- HDF – Hierarchical Data Format, Developed at the National Centre for Supercomputing Applications (NCSA). The HDF project involves the development and support of software and file formats for scientific data management. The HDF software includes I/O libraries and tools for analysing, visualising, and converting scientific data.
- XML – Extensible Markup Language (defined by the W3C) is a meta-markup language that provides a format for describing structured data through the use of a schema (URL 3). The aecXML schema (developed by Bentley Systems Inc.) is meant to facilitate communication of information between the various constituents involved in the architecture, engineering & construction process. The LandXML schema (developed by Autodesk Inc.) is meant to transport design data between various software products and technologies involved in the Land Planning, Civil Engineering and Land Survey process.

The first two, which are construction industry related, have been successfully demonstrated in several European projects such as ATLAS, COMBI, COMBINE and CIMsteel (Wix, 1997). XML is possibly the future standard for data communication on the Internet as it allows custom schema to be defined and exchanged, making it possible to develop lightweight and flexible versions of other data structures such as those mentioned above. For the purpose of the prototypes described below an ASCII file format was adopted and combined with a custom data structure to reduce development time.

5.5 Customisation & Presentation Techniques

From the observational study undertaken and mentioned earlier, it is apparent that as well as the key tasks identified, engineers often perform a variety of custom tasks such as data checking (i.e. checking averages against rules of thumb) and formatting. These tasks were often performed to satisfy curiosity/doubts in the output and to aid visual recognition of key data (i.e. highlighting maximums). It is therefore considered important that customisation is supported by the visualisation application. The presentation of the results is key to the effectiveness of the application. Extensive work has been carried out in this field and the authors are currently identifying techniques most applicable to building performance data. Therefore for the purpose of the prototype, methods already familiar to the engineers were utilised; this included basic charts, tables and colour coded scales.

6. PROPOSALS

As a result of the observational study two applications were proposed:

- a method to automatically process the output within a *spreadsheet* (MS Excel), aiding the engineer to gain a quick and efficient insight into the data. The spreadsheet tools were developed over a period of several months and then released to all users of the analysis tools.
- a prototype web-based application, designed to display the solution in a three dimensional *virtual environment* to aid spatial recognition and data navigation. This was developed over a slightly longer period of 1 year.

6.1 Spreadsheet

The immediate need to improve the efficiency of data navigation and presentation has been identified and several macros for Microsoft Excel have been produced (written in Visual Basic for Applications). These are application-specific as they rely on the position of the data within the output remaining in a fixed, pre-determined, position. Key functionality includes:

- Format & Graph: This macro applies formatting to each cell of the spreadsheet to clearly define table extents and key data. The macro also creates graphs of a given day's results (air temperature, airflow rate and solar radiation) with the relevant headings and legends.
- Comparison: The most important aspect of design analysis is often the comparison of options (Lebrun, 1998); this macro therefore allows multiple sets of results to be compared (tabular form) and plotted automatically.
- Jumping and Printing: This macro improves navigation of data by facilitating the ability to jump the cursor to a given section of data by simply clicking a link to it. Printing has also been improved by defining a pre-set format for each table of results and allowing headers and footers to be automatically generated from the files information (important for Quality Assurance).

6.2 Virtual Environment

The thermal analysis of a building is inherently a multidimensional problem, from the initial concept through the isometric or perspective sketch, and to the three-dimensional analysis model. However, this is presently where the '3D' chain ends, as the majority of analysis output is presented in a static two-dimensional format such as tables and graphs. The focus of this study is to build on the natural affordance provided by virtual environments to aid the presentation of analysis results. The project originally identified VRML as an ideal technology for representing a building's physical form whilst having the ability to link key elements to the relevant results. However, towards the end of the study a proprietary 3D Internet technology was identified as having additional scope. The following sections detail the use of each of these technologies within a prototype system.

6.2.1 VRML

The prototype (Visual Basic Viz Application) presented here is designed to read geometry/ results files produced by an in-house analysis program and produce the desired visualisation, indicated by the dashed box in *Figure 2*.

The format of these files is presently application-specific, although future work will be based on the aforementioned standards, thus allowing other analysis programs to be coupled to the system.

The visualisation consists of:

- Default web page – includes an overview of the system and navigation instructions.

- Framed web page – consisting of the following frames.
- Navigation Bar –links to predefined camera positions and analysis data.
- Results Overview –an overview of the selected room's surface details.
- Results Display –detailed results for the selected object (room, surface or window).
- 3D Content – in this case contains a VRML representation of the building's geometry (based on the analysis model).

When constructing (within the VB Viz Application) the files necessary to produce the visualisation, the user is given several customisation options, such as: preview of the floor plan to locate information points (red/dark sphere in the foreground of *Figure 4*.), positioning of default cameras and other custom settings such as graph size.

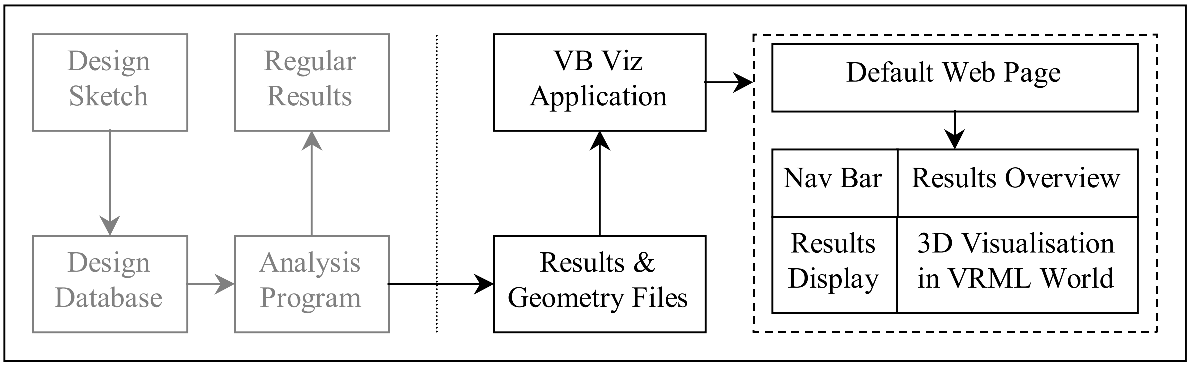

Figure 2. Process Model - VRML Prototype

6.2.2 Proprietary Technology

In order to take advantage of the improved visual quality offered by the proprietary product it was necessary to modify the prototype in the following ways:

- VRML file creation was disabled.
- A generic world was created in the proprietary software's editing environment and added to the prototype. This world contains the objects and script necessary to read the geometry file and create a custom world (a replica of the VRML 3D model).
- Add code to automatically run the above script and save the resulting 3D file.
- The 3D content frame was linked to the 3D file.

Figure 3 illustrates the new process model; note the result/geometry files have the same origin and remain constant in both content and format.

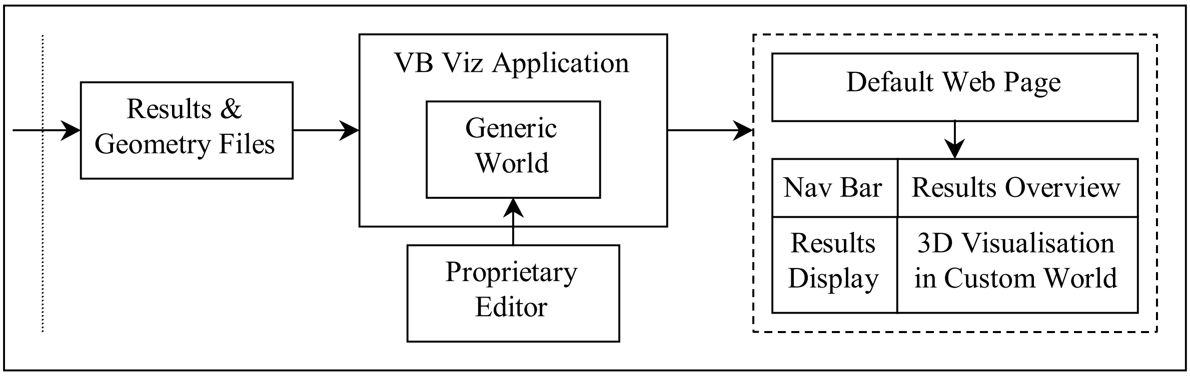

Figure 3. Process Model – Proprietary Software Based Prototype

The remainder of the project remained unchanged from that detailed in the VRML section, the final product can be seen in *Figure 4*.

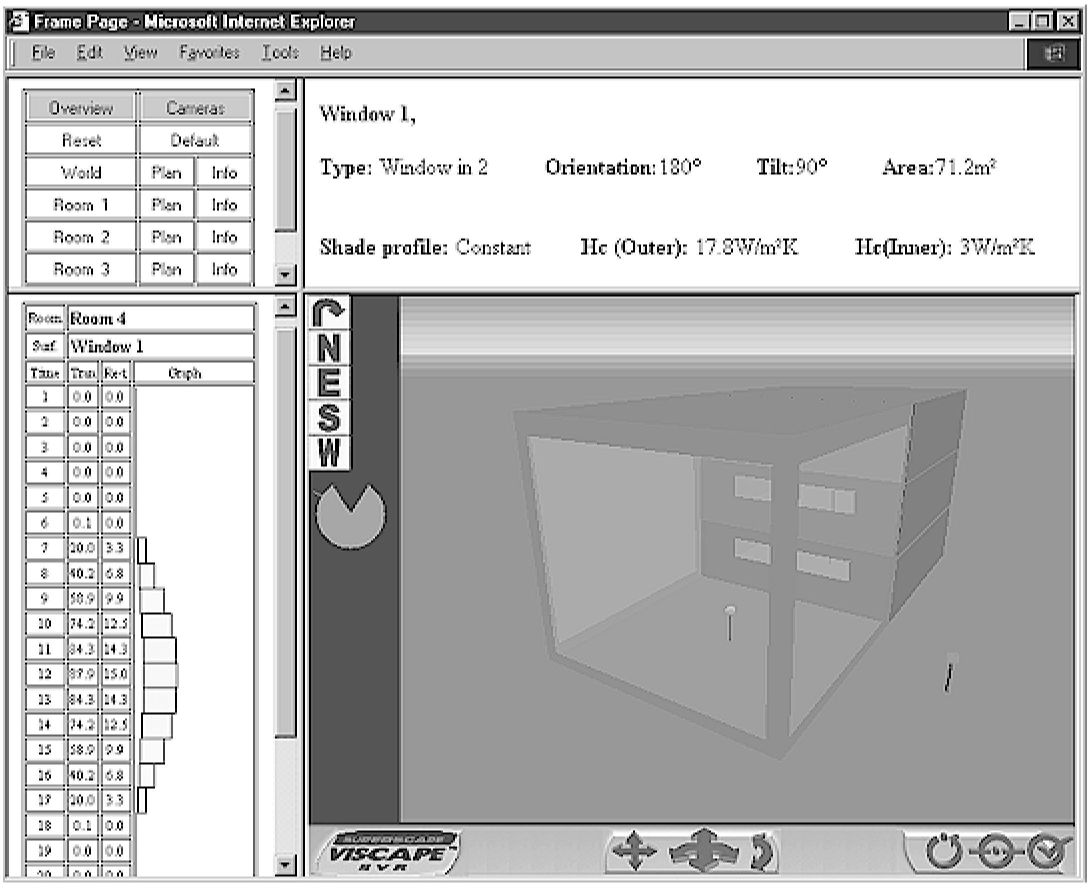

Figure 4. Screenshot – Proprietary Software Based Prototype (4-room model)

7. USER TRIALS

Following the completion of the spreadsheet and virtual environment applications, quantification of their effectiveness was sought through a series of user trials. The trials consisted of three small groups of users completing an identical set of tasks using the following output mechanisms:

- Group 1: Plain spreadsheet, control group.
- Group 2: Spreadsheet with macros applied as in *Section 6.1*.
- Group 3: Virtual Environment, proprietary software based prototype as in *Section 6.2.2.*

Tasks were based on the location and use of analytical produced by an in-house thermal simulation tool; a total of 44 tasks were set, examples of which are:

- How many translucent surfaces (Window(s)) are there in the room?
- Which room has the highest maximum air temperature?
- Which opaque surface has the highest maximum surface temperature?
- Why is this likely to be the hottest surface in this room?

All subjects were familiar with these tasks and, in the case of Groups 1 and 2, they were also familiar with the output mechanism. In the case of Group 3 a ten-minute training session was given to familiarise the subjects with both movement and location of results within the three-dimensional environment. The tests were managed by custom software developed to deliver each task in turn, monitor the given response and record the time taken. In addition to this the software recorded the users response to a usability statement, See *Figure 5.*

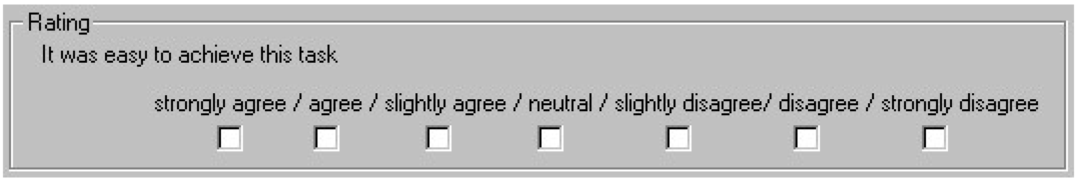

Figure 5. Usability Software - Rating based on a seven-point scale (Preece, 1994)

8. USER TRIALS RESULTS

Each test took approximately one and a half hours to perform. The results were collated and processed to remove rogue data and mark the accuracy of the given answers. Correct answers were assigned one point and incorrect answers zero. The average accuracy and rating for each group was taken for all tasks and is given in *Table 1.0.* The results indicate both increased accuracy and perceived usability for Groups 2 and 3 when compared to the control group (Group 1). In addition to which there is some improvement in the consistency of the accuracy and the feeling that the software supported the given task. The virtual environment software (Group 3) achieved the best results in both cases, however the difference between this and the preformatted spreadsheet group (Group 2) is only small.

	Group 1		Group 2		Group 3	
	Mean	SD	Mean	SD	Mean	SD
Accuracy (%)	76.4	30.5	87.5	22.5	89.3	24.2
Rating (7 = Easy, 1 = Hard)	3.36	1.05	4.72	0.80	4.84	0.60

Table 1. User Trials – Accuracy and Rating Results

The average of 'the time taken to perform each task' was then calculated on a group by group basis. These values were then summed task by task to give the total accumulative time taken by each group to complete all tasks (including incorrect answers), *Figure 6*. The trend lines (linear, all r^2 values > 0.99) indicate there is no significant difference between Groups 2 and 3 response times, while there is a clear improvement over the control group (Group 1). Conversely, if the data for incorrect answers is removed the results for the two spreadsheet-based solutions (Groups 1 & 2) show similar performance characteristics while the virtual environment prototype indicates improved performance, *Figure 7*. The latter figure includes polynomial trend lines with r^2 values greater than 0.99). Due to the limited number of participants it has not been possible to collate meaningful data for the analysis of memorability or learnability. These measures are seen as more subtle and will require a larger study to produce accurate results.

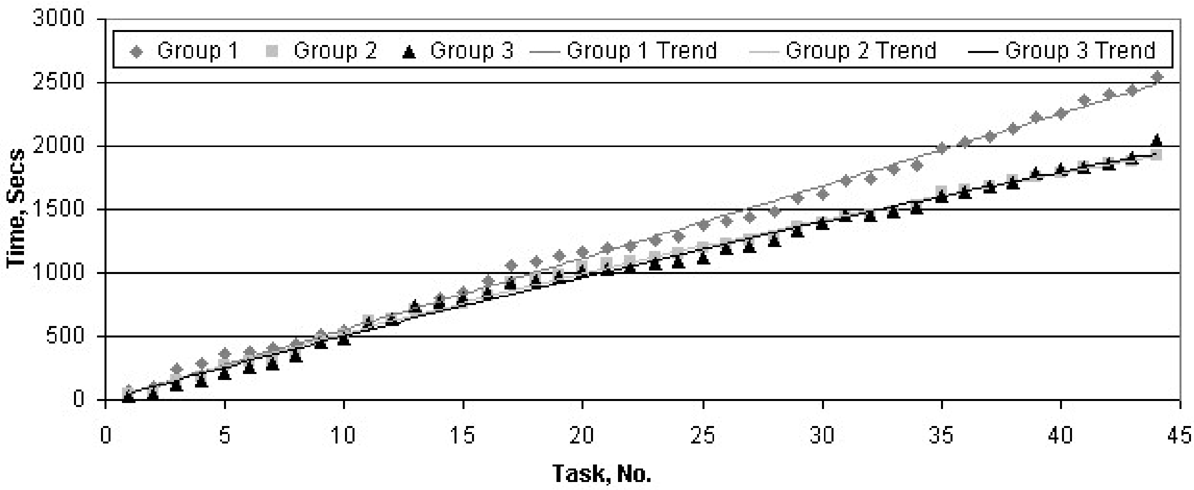

Figure 6. User Trials – Accumulative time for <u>all</u> answers

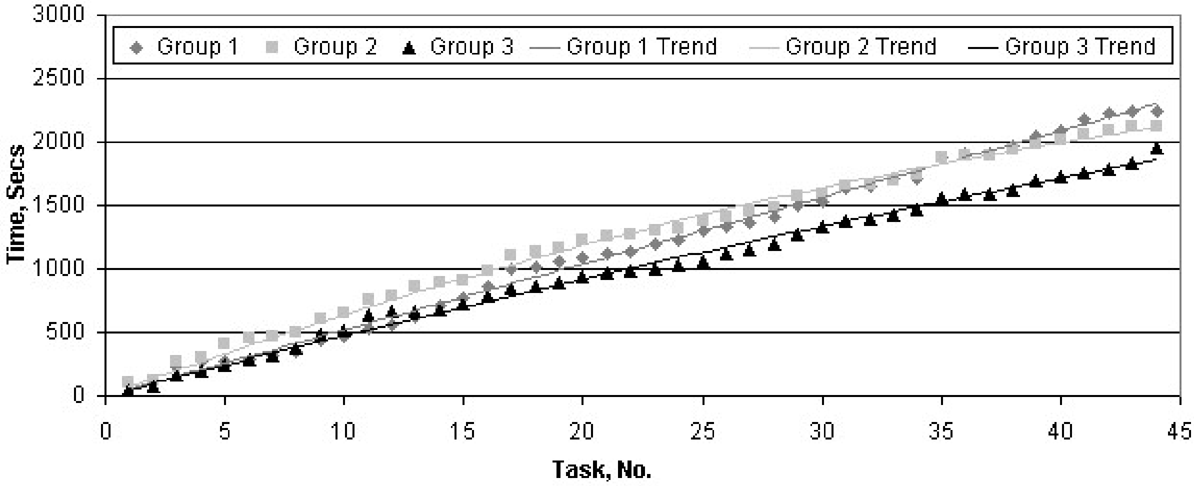

Figure 7. User Trials – Accumulative time for correct answers

9. CONCLUSION

Nielsen (1993) suggests that software usability is closely associated with five factors:

Efficiency – The virtual environment prototype has shown improved performance by a reduction in the time taken to both correctly and incorrectly perform the given task.

Satisfaction – The user ratings suggest that the majority of users felt the virtual environment prototype was most effective in supporting the given tasks, making them 'easy' to complete.

Learnability & Memorability – The data collected was insufficient to clearly measure the effects of learning or remembering tasks. The increased performance of the virtual environment prototype is based on a range of factors which are likely to include elements of learning, but will also be largely based on improved support of searching and locating data.

Errors – The virtual environment prototype has been shown, on average, to support greater accuracy than the spreadsheets used within the control group.

This study has highlighted the potential benefits of scientific visualisation for the representation of building performance data. It has also provided a useful model for which to develop further tests to improve the way in which we measure such benefits. Further to this, several observations were made during testing:

- Users became disorientated within the virtual environment and often misunderstood the compass facility.
- The majority of users within Groups 1 & 2 (spreadsheet output) did not make use of built in mathematical functions such as MAX, which can be used to locate a maximum value e.g., a surface temperature.
- Users in Group 3 were not sufficiently familiar with the virtual environment to perform some of the tasks. Future work will look at the effects of training on group performance.
- The atmosphere in the training room when Group 3 performed the test was noticeably jovial, with comments like 'hey look you can fly upside down!'.

Each of these observations will be used to refine and ultimately develop a method for assessing the performance of future prototype visualisation systems.

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URL 4, http://www-personal.umich.edu/~jrender/Thermal/index.html