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The Application of Visualisation Techniques to the Process of Building Performance Analysis

Matthew John Pilgrim
THE APPLICATION OF VISUALISATION TECHNIQUES TO THE PROCESS OF BUILDING PERFORMANCE ANALYSIS

By
Matthew John Pilgrim

A Dissertation Thesis submitted in partial fulfilment of the requirements for the award of Engineering Doctorate (EngD) of Loughborough University

[September 2003]
CERTIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this thesis, that the original work is my own except as specified in acknowledgments or in footnotes, and that neither the thesis nor the original work contained therein has been submitted to this or any other institution for a higher degree.

Matthew Allen  
(Signed)

11/11/03  
(Date)
ACKNOWLEDGEMENTS

I would particularly like to thank Mike Prince for sanctioning this research and Mike Holmes for his continuous and undoubting mentorship. I also thank my academic mentors Nasreddine Bouchlaghem and Dennis Loveday for their guidance.

The Sponsoring company, Arups, and its staff have been most generous to me throughout the research, thank you. I’m especially grateful to all those who took the time to participate in surveys and battle with early prototypes. I am also thankful to Matt Collin, James Tan, Josh Macabuag and Roger Marsh who all helped with some aspect of prototype development.

The final thank you goes to my fellow Research Engineers for keeping me sane, my beautiful wife Clare for putting up with me and my extended family for listening to my ramblings.
ABSTRACT

Visualisation, the representation of data in visual form, is at the core of our ability to communicate information. Without clear representation, data would remain in its raw form thus greatly hindering the communication process. This is especially the case when the data source is large, complex and subject to change. One such area is related to the use of computer based simulation tools for thermal analysis.

This research investigates the potential of visualisation to improve the ways in which thermal analysis data are presented to building services engineers, with a view to increasing the accuracy and efficiency of its interpretation. The approach taken throughout followed a pattern of research, development, demonstration and evaluation. The research phase included a detailed review of existing visualisation theory and an extensive user requirement survey. The development phase produced three working visualisation software prototypes, each of which was demonstrated or evaluated within the sponsoring company.

Whilst the initial emphasis of the research was advanced Three-Dimensional (3D) visualisation, extensive user requirement analysis indicated that comparing multiple datasets in an intuitive manner was more important. In response, the research focused on combining techniques in ways which supported the rapid comparison of multiple files and the data contained within. The final prototype combines techniques for data storage and manipulation with information visualisation techniques and advanced 3D graphics. These elements are tightly integrated within a single application that facilitates the management and interpretation of data from multiple analysis models. Evaluation of the prototype showed high levels of user satisfaction and improvements in the accuracy and efficiency of data interpretation. The techniques demonstrated by the prototype were also understood and liked by the users of thermal analysis tools. Several of the techniques, such as the new Force Directed Difference Diagrams, have potential applications outside of building services engineering. The research has demonstrated it is possible to improve the representation and interpretation of building performance data using visualisation techniques.

KEY WORDS
Building, Analysis, Data, Visualisation, Representation, Survey, Prototype, Evaluation, Three-dimensional (3D), XML
The research presented within this thesis was conducted to fulfil the requirements of an Engineering Doctorate (EngD) at the Centre of Innovative Construction Engineering (CICE), Loughborough University. At the core of the EngD is the solution of one or more significant and challenging engineering problems within an industrial context. The main essence is the development of innovative thinking, while tackling real industrial problems\(^1\). As such the researcher is located within a sponsoring organisation (known from here on as the “sponsor’s”) with regular academic support in the form of quarterly meetings.

The EngD is examined on the basis of a Thesis containing at least three (but not more than five) publications or technical reports. Presented within this thesis are two conference and two journal papers plus an additional unpublished paper. Each paper is referenced by a Paper Number (1-5) and the appendix where it can be located.

\(^1\) Extracted from text available on the CICE website (www.cice.org.uk)
## ACRONYMS / ABBREVIATIONS

<table>
<thead>
<tr>
<th>3D</th>
<th>Three-dimensional</th>
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<tr>
<td>EngD</td>
<td>Engineering Doctorate</td>
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<tr>
<td>CICE</td>
<td>Centre of Innovative Construction Engineering</td>
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<tr>
<td>PAM</td>
<td>Performance Assessment Methods</td>
</tr>
<tr>
<td>HVAC</td>
<td>Heating, Ventilation and Air Conditioning</td>
</tr>
<tr>
<td>ROOM</td>
<td>A single zone thermal analysis program called Room</td>
</tr>
<tr>
<td>VR</td>
<td>Virtual Reality</td>
</tr>
<tr>
<td>AR</td>
<td>Augmented Reality</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronic Engineers</td>
</tr>
<tr>
<td>RAD</td>
<td>Rapid Application Development</td>
</tr>
<tr>
<td>ACM</td>
<td>Association of Computing Machinery</td>
</tr>
<tr>
<td>PDA</td>
<td>Personal Digital Assistants</td>
</tr>
<tr>
<td>IFC</td>
<td>Industry Foundation Classes (note: IFCs define object types and related concepts which support the core exchange needs of the building industry).</td>
</tr>
<tr>
<td>XML</td>
<td>eXtensible Mark-up Language (note: this is a representation mechanism for storing and transporting data. It is not a definition of the data or it’s structure, this is defined by a schema. A schema may be user defined or based on an industry standard such as ifcXML).</td>
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Background to the Research

1 BACKGROUND TO THE RESEARCH

1.1 PROBLEM DEFINITION

According to Gallagher (1995, pp. 13) the “rapid growth of visualisation applications in the engineering field results in large part from its tangible benefits within the design process”. This statement is supported by a list of how visualisation techniques have affected engineering practice, summarised as:

- **Decreased physical testing** – computer simulation produces a decrease in physical testing and the costs associated with it. Computer simulation allows engineers to observe phenomena which may be expensive, difficult or dangerous to reproduce physically.

- **Greater integration of design analysis** – the better one can visualise analysis results, the easier it is to modify a design to correct flaws shown by the analysis.

- **Increased analysis complexity and sophistication** – digital numerical analysis has always been limited by the ability to visualise its results. Newer 3D visualisation techniques in particular have made it possible to examine complex phenomena which are not readily seen on an analysis model.

- **Design optimisation** – analysis has evolved from a tool for evaluating static designs to a means of optimizing the design itself. Visualisation allows engineers to evaluate automated design changes and analysis results.

- **Productivity and accuracy** – improved visualisation tools allow a faster and more thorough design process. More accurate control of the result data seen by the engineer can lead to better design decisions and a clear economic benefit in design productivity.

A number of engineering disciplines have already benefited from these attributes, one example being automotive engineering. Here, complex and dynamic datasets are produced by the simulation of crash test worthiness, cockpit acoustics, aero dynamics and engine vibration. In response to the increase in model complexity and the quantity of data produced by these simulations, facilitated by advances in computation power, automotive manufacturers such as Ford and BMW have invested in visualisation systems (Schulz 1998 and Stewart & Buttolo 1999). This has led Schulz to state that ‘virtual environments for car-body engineering applications provides insightful, intuitive visualisation of virtual prototypes and allow effective communication between engineers and management”.

In recognising the ability of visualisation to improve the accuracy, efficiency and communication of simulation in certain fields, it becomes desirable to investigate its application to other fields and to other types of analysis. One such analysis, which produces similarly large and complex data sets, is that of a building’s thermal performance. The research presented here investigates the potential benefits of applying visualisation techniques and technologies to the data generated by building thermal performance analysis tools. Improved representation of these data will lead to a greater understanding of the building’s likely performance and in turn a refined design.
1.2 GENERAL SUBJECT DOMAIN

1.2.1 BUILDING PERFORMANCE ANALYSIS

The term ‘Building performance’ incorporates; aesthetics, economics, stability, environment, air tightness etc. This research is limited to buildings’ internal thermal environments and the energy required to achieve the desired conditions. The analysis of this is important for the design of comfortable and economical buildings (Hong et al 2000). Modelling and simulation are techniques for evaluating building performance. Modelling is the art of developing a faithful representation (model) of a complex system. Simulation is the process of using the model to analyse and predict the behaviour of the real system (Elzas 2002 and Zeigler 1976). Whilst simulation can be conducted in a number of ways, including physical models, it is the use of computer based digital models that have prevailed in the field of design (Hensen 1991). Building analysis software can be used to predict the dynamic thermal response and performance of buildings and to assess and compare the effects of different design options (AM11 1998). A recent survey of energy design packages (BRECSU 2002) identified two main categories of software based tools, Simulation and Sizing. The objective of sizing tools is to calculate the ‘size of the plant’ for given combinations of space, climate and occupancy. Whereas simulation tools predict performance under ‘realistic’ operating conditions for a period of up to a year. It is the complexity of data associated with simulation tools that this research is concerned with. The simulation of a building and its components may be conducted using a number of different software based tools, these are broadly categorised into the following types:

- **Single element** – Models of conduction, convection and radiation are used to predict heat transfer within building elements such as cavity walls and ventilated glazing systems.
- **Single zone** – Single zone models are used to predict the likely thermal performance of a space and its surrounding surfaces. These values can in turn be used to drive the calculation of internal airflows and occupant comfort.
- **Multi zone** – The thermal performance of multiple zones is coupled to models of heating, ventilation and air conditioning (HVAC) plant to predict likely building energy consumption.

It is normal for a multi zone model to encompass a, sometimes simplified, single zone model which in turn incorporates a single element model. In this way an entire building and all its significant surfaces may be analysed to predict likely thermal performance and HVAC plant energy consumption. Note that a single zone, if modelled appropriately, may represent a whole building or one or more adjacent spaces. Research related to building performance analysis has, up until the last 10-15 years, focused primarily on the fundamental algorithms used within the simulation tools (Hong et al 2000). The tools were therefore designed and used primarily by researchers, resulting in slow industry take up (Wilde 1998 and Robinson 1995). However, more recently the research has focused on refining the usability of the tools (Annex30 1998) and transferring them to professional practice (Bartholomew et al 1997). The driving force for this, is the view that, these tools should not only be used for final performance confirmation but as an integrated element of the design process within the design practice (Augenbroe 1992, Holm 1993 and McElroy & Clarke 1999).

The use of simulation in the design process raises questions about the accuracy of analytical results. There are several sources of error in the analytical process, these can
be grouped into two types; internal and external errors (Judkoff 2003). Internal errors occur due to the [inadequate] representation of complex heat transfer mechanisms, inaccuracies in mathematical solutions and coding errors. External errors are related to mistakes and assumptions made when inputting data and interpreting the output data. These can be much greater than, and hence swamp, any internal errors (Annex21 1994). This is a significant problem, not only for the evaluation of analytical tools but also their use in design. In selecting a simulation tool there becomes a point where a more accurate tool may produce less accurate results due to the increase in input required to construct the numerical model and the error associated with that input (Chapman 1999). Thus far, research into user induced error has focused primarily on mistakes and approximations made when entering the numerical model with little work investigating the effects of the user misunderstanding/misreading the model's output (Bloomfield 1988). In an attempt to reduce both types of error, and the variability between the results obtained by different users of the same tool, quality assurance procedures were developed. These procedures, in the form of Performance Assessment Methods (PAMs), were designed as a way of documenting the purpose of a simulation and the methods used in carrying it out (Annex21 1994). PAMs can reduce the number of errors made during an analysis (Wijsman 1994) but have the greatest potential when used in conjunction with a quality assurance system. The International Energy Agency’s report on appropriate use of programs (Annex21 1994) therefore recommends a procedure for those regularly carrying out performance assessments, see Table 1.

Table 1 – Routine procedure for carrying out performance assessments (Annex21 1994)

<table>
<thead>
<tr>
<th>No</th>
<th>Procedure</th>
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<tr>
<td>1</td>
<td>The person carrying out the calculations should make sure that the input data (files) are checked thoroughly with the PAM data and building specifications. If possible choose material and building components' properties from a built-in database. Visualise building geometry and check it, if possible.</td>
</tr>
<tr>
<td>2</td>
<td>Document the errors and blunders found. Such a log book can be used in setting up some routine checks of the areas that are most prone to error. After sufficient data has been collected in such a log book, an analysis can be made and areas that need routine checks will be identified.</td>
</tr>
<tr>
<td>3</td>
<td>If possible, a second person should be asked to check the input data according to the PAM and building specifications and add the errors found to the log book.</td>
</tr>
<tr>
<td>4</td>
<td>A test run is carried out and all results (and not only the results that are of direct interest to the PAM) are analysed. One should always look for unexpected results. If possible produce a Sankey diagram (a diagram shown all energy sources and sinks) and inspect it. For example by examining such a diagram and comparing the relative magnitude of energy gains and losses associated with main building components, e.g. window, floor etc., it is possible to identify major possible errors.</td>
</tr>
<tr>
<td>5</td>
<td>If possible, carry out simple tests, comparing steady state calculations. Do the same for thermal mass tests.</td>
</tr>
<tr>
<td>6</td>
<td>If the output capability of the program allows, the PAM user should check the energy balance at the air or zone node for important zones, or if possible, for the entire building.</td>
</tr>
<tr>
<td>7</td>
<td>If possible, compare with examples from previous similar jobs.</td>
</tr>
<tr>
<td>8</td>
<td>Make sure that the versions of the program, data files, weather files, etc. correspond to the final design and have been checked. Good housekeeping is essential.</td>
</tr>
</tbody>
</table>
This table identifies a number of important requirements; visualising the buildings geometry (Row 1), conducting a peer review (Row 3), gaining an overview of all results (Row 4), the visual presentation of results associated with components (Row 4) and the comparison of multiple sets of results (Row 7). Whilst the PAM stresses the need to document the analytical input, the procedure recommended in Table 1 has a clear emphasis on the presentation of the model and the associated results. A number of other research efforts have identified the requirement to improve the presentation of output data but the guidance given is lacking in detail, for example: “present all [like] results in the same format” (Wijsman 1994), “provide easy-to-use option to specify particular output parameters in tabular or graphical form” (Bloomfield 1988) and “provide a) Simple diagrams, b) Improved datasheets with graphics & data and c) Brochure like compilations of solutions for special problems” (Annex30 1998).

The output capability of thermal analysis tools differs tremendously. Whilst only the more sophisticated tools offer the ability to display the results within the program nearly all tools make the raw data available for further processing. It is therefore usual for an engineer to import the data into a post-processor, typically a spreadsheet package, to carry out additional calculations or produce specific graphical representations.

To summarise:
- Building performance analysis is becoming an important design tool.
- It is possible for two users to analyse the same building, with the same simulation package, but obtain different results due to input and output errors.
- Input errors have been more extensively researched than errors made in the interpretation of output data.
- A limited number of high level suggestions have been made for improvements to simulation output interfaces.

The research presented here further investigates the requirement to improve the representation of building performance analysis data and identifies suitable visualisation techniques for doing so.

1.2.2 VISUALISATION

“Computer visualization methods have emerged as the most effective tool for rapidly communicating large amounts of information to scientists and engineers in a format that enhances comprehension and deepens insight”

Haber & McNabb 1990 (pp. 74)

Visualization is not a new phenomenon, it has been used in maps, scientific drawings, and data plots for over a thousand years. Examples include a map of China dated 1137 a.d. (Needham 19592) and the famous map of Napoleon's invasion of Russia produced in 1812 a.d. by Jaque Minard (Tufte 19833). Most of the concepts learned in devising these images carry over in a straight forward manner to computer visualisation. In reality visualisation depends on the integration of a number of older technologies, including: computer graphics, image processing, computer vision, computer-aided design, geometric modelling, perceptual theory/psychology and user interface studies (Haber & McNabb 1990). These are combined to provide greater insight and

---

2 Image available at http://www.henry-davis.com/MAPS/EMwebpages/218.html or 218a.html
understanding of the data and facilitate its presentation/communication to others (Larkin et al 1997 and Card & Mackinlay 1997). Visualisation is defined by Card et al (1999) as:

“The use of computer-based, interactive, visual representations of data to amplify cognition”.

Visualisation can be further divided into Scientific Visualisation and Information Visualisation. Scientific visualisation is applied to physically based data, whilst information visualisation is applied to more abstract, non-physically based data (Card et al 1999 and Spence 2001), see Figure 1.

A) Temperature within a glazing mullion under summer and winter conditions.

B) Visualisation of the nursery rhyme ‘Mary had a little lamb’.

Figure 1 - Examples of Scientific (A) and Information (B) Visualisation [Both by candidate]

Scientific visualisation generally uses the location of each data point plus a number of encoding techniques to form the representation. Information visualisation techniques require additional algorithms to map the data points to a location within the representation prior to their encoding. In the example given above, the individual words of the nursery rhyme were positioned around the edge of a three-dimensional spiral, thus giving it a physical dimension.

Due to the diverse nature of visualisation a large number of techniques have been developed, these have been reviewed and classified by numerous authors. Examples include those related to; visualisation in general (Lohse et al 1994 and Keim 2001), information visualisation (Spence 2001, Ware 2000, Ng 2000, Geisler 1998 and Hollan & Bederson 1997), scientific visualisation (Keller & Keller 1993 and Haber & McNabb 1990), presentation graphics (Tuft et al 1983, Tuft 1990, Tuft 1997, Harris 1999, Bounford & Campbell 2000, Wilkinson 1999 and Wilkinson 2001), multi-dimensional visualisation (Hoffman & Grinstein 2001, Wong & Bergeron 1997 and Grinstein 2001) and graph [Network] visualisation (Herman et al 2000). Of particular interest, because of its relationship to 3D geometry, is scientific visualisation. Scientific visualisation is closely associated with Virtual Reality (VR) as it shares many of the same attributes. VR, as a medium, has three main properties (Whyte 2002):
• Interactive - users can interact with models;
• Spatial – models are represented in three spatial dimensions;
• Real-time – feedback from actions occurs without noticeable pause.

VR, as a system, consists of hardware and software components (Brooks 1999). The hardware generally includes a number of input and output devices (e.g. joysticks and head mounted displays). The software generally consists of separate tools to author and interactively display the 3D environment (also referred to as a virtual environment). Scientific Visualisation and VR both facilitate interactive visual representation to amplify the cognition of data and spatial layout (Watts et al 1998). These attributes appear to match the primary requirement to display data, some of which is 3D, to the engineer to aid their understanding of the simulation results.

1.3 CONTEXT OF THE RESEARCH

1.3.1 BUILDING PERFORMANCE VISUALISATION


Examples of more advanced building performance representation are found in research/teaching tools such as ECOTECT and The Building Performance Advisor (BDA). ECOTECT, developed primarily by Dr. Andrew Marsh4 as a teaching aid, supports a number of performance analysis functions at the conceptual stage. The software consists an intuitive 3D modeling package and a number of integrated techniques for representing the analytical results. These, where possible, are calculated in real-time and displayed interactively within the modeling environment. For example, indicators of occupant comfort are plotted on the floor plane. However with regard to thermal analysis the results appear restrained to two dimensional graphics. The BDA, from Laurence Berkley Laboratories5, also uses two dimensional graphs but combines these with three dimensional graphs in an innovative ‘Decision Desktop’. The desktop allows users to compare a number of performance parameters for a number of alternative solutions. This is achieved through a matrix of graphics, one for each

4 Square One research PTY LTD & Welsh School of Architecture (Cardiff University)
5 Contact Konstantinos Papamichael (K_Papamichael@lbl.gov) or visit http://gaia.lbl.gov/bda/
combination solutions and parameters, See Figure 2.Whilst useful for gaining an overview of the datasets the method requires significant screen area and is not good at highlighting subtle differences. Three-dimensional plots similar to those in the BDA are also used in Solar-5, an energy simulation tool described by Milne et al (2001).

Figure 2 - Building Design Advisor Decision Desktop (Source: program documentation)

Whilst the tools and applications presented indicate the potential of visualisation techniques to improve the representation of data there appears to be little investment in implementing these in mainstream thermal simulation packages. It is the desire to benefit from these visualisation techniques that led the industrial sponsor to participate in the research of their application to building performance data.
1.3.2 **INDUSTRIAL SPONSOR**

Arups is an international engineering consultancy consisting of nearly seven thousand staff. Its business is spread across several divisions each consisting of a number of groups. The research presented here is sponsored and co-ordinated by the Research & Development Group who, with the Engineering Software Group, are responsible for the development of all in-house thermal and energy analysis tools. This includes the development of a single zone thermal analysis program called ‘ROOM’ (Holmes & Conner 1991), See Figure 3.

![Figure 3 - ROOM output: Sun patches and Comfort distribution](image)

ROOM is used by the sponsor’s building services engineers to investigate the impact of design decisions on factors such as internal temperatures, ventilation rates, occupant comfort, solar distribution and space energy consumption in buildings. The basic ROOM algorithm makes use of what is known as an explicit method (mathematically - forward finite differences). Essentially this means that conditions in the future are predicted from the current state. ROOM is a dynamic thermal model, this means that storage of heat within building elements is taken into consideration. The model employed in ROOM assumes that a wall can be represented by a number of small ‘elements’ in series. Each element can both store and conduct heat. The elements are assumed to be sufficiently small that each is at a uniform temperature. Heat losses and gains to rooms are closely linked to the radiation exchanges that occur within the space. The effects of radiant exchange between room surfaces is often not realised. While the physics of radiant heat transfer are well understood their application to buildings is...
often neglected. Indeed it is this aspect of heat transfer that causes most arguments when the calculation of steady state heat loss is discussed. ROOM avoids the problem by going back to the fundamental equations of short-wave and long-wave radiation.

The goal of using ROOM is to optimise the design of a building and to calculate the required characteristics of that building and its key components. Components include but are not limited to:

- Surface shape and fabric.
- Window shape, fabric, location and shading.
- Zone environmental set points.
- HVAC plant type, capacity and control.

ROOM, like many other single zone tools:

- requires a significant amount of input data (both numerical and geometrical),
- produces a large array of numerical output data for periods of time ranging from one hour to one year,
- is used iteratively to produce a number of possible solutions,
- is useful only when the engineer can draw meaningful information from the data produced.

Thermal analysis programs, such as ROOM, are now extremely powerful, relatively inexpensive to purchase and have the potential to dramatically improve the environmental performance of buildings (Annex21 1994). At present, the representation of data produced by ROOM and similar tools is limited in a number of ways. Most do not specifically support the engineer in their interpretation tasks, making it necessary to repeatedly carry out actions which may be easily provided for or automated. The candidate’s experience in developing thermal analysis software for the sponsoring company confirmed the engineers’ reliance on spreadsheet packages for the manipulation and representation of the thermal analysis data. Whilst tools were provided to aid this process, their design was constrained by the capabilities of the spreadsheet package. The primary restraint was the inability to present the 3D form of the building as entered by the engineer for the purpose of the analysis. This is required if we assume that, to adequately visualise the results produced by building thermal analysis, it is necessary to represent them alongside associated input data, which includes the zone’s 3D geometry. This assumption is based on the necessity to:

- Ensure links between the cause (input, e.g. surface fabric) and effect (output, e.g. surface temperature) are displayed as clearly as possible.
- Closely associate the data with the object it relates to, i.e. each surface temperature displayed on or linked to the appropriate surface.

The motivation for the research presented is to investigate the potential of displaying the zone’s geometry in 3D alongside the data produced by ROOM, as a means to aid interpretation. Furthermore it is important to gain a better understanding of user requirements and of available visualisation techniques to help improve the way in which building services engineers interpret and present thermal analysis data.
2 AIM, OBJECTIVES & METHODOLOGY

The aim of the research is:

To investigate the potential of visualisation techniques to improve the representation of data that forms the output from building thermal analysis programs.

Improvements in this area will lead to a better and more efficient use of simulation programs by facilitating the interpretation of analysis data by construction industry professionals, leading, in turn, to more informed design decisions and improved communication. The research aim is supported by three objectives, each of which was achieved through a number of distinct work packages.

2.1 OBJECTIVES

2.1.1 OBJECTIVE 1 – REVIEW CURRENT PRACTICE

Review current practice and requirements for the representation of building performance data.

The first objective was to investigate visualisation techniques currently supported by building analysis software and data representation practice within the sponsor’s company. In addition, this objective was to establish whether there was a requirement to improve building performance data representation. The objective was met by the completion of the ‘Current Practice Review’ and ‘User Requirements’ work packages.

2.1.2 OBJECTIVE 2 – IDENTIFY SUITABLE TECHNIQUES

To identify visualisation techniques and technologies suitable for the representation of a building’s 3D form and the interpretation of the related output data.

The second objective was to become acquainted with visualisation techniques and technologies and identify their potential applicability to the problem domain. This ensured that the research focused on state of the art solutions which were relevant to the sponsors operations. The objective was met by the completion of two work packages. The first, ‘Visualisation Demonstration Projects’, identified and evaluated a number of key technologies. The second, ‘Extension of visualisation principles to building performance data’, reviewed visualisation techniques and proposed a number of conceptual models for their application to building performance data.

2.1.3 OBJECTIVE 3 – APPLY AND EVALUATE TECHNIQUES

To demonstrate the application of suitable technologies to the geometry and data produced by the sponsor’s software, and to evaluate its potential for improving interpretation of output data.

The third, and final, objective was to demonstrate and evaluate, in an industrial context, solutions designed to improve the representation of the sponsor’s building performance data. These solutions were based on the techniques and technology identified in Objective 2 and designed to meet the user requirements identified in Objective 1. The objective was met by the completion of the ‘Solution Development, Application and Testing’ work package.
2.2  METHODOLOGY

The methodology adopted to meet the research objectives is presented according to the work packages identified above.

2.2.1  WP1 - CURRENT PRACTICE REVIEW

A state-of-the-art review of building performance visualisation was conducted to establish which techniques were available to engineers within existing tools and which were being researched. A further review was conducted within the sponsoring company to establish which techniques were used and how these were developed to meet the engineers’ requirements.

2.2.2  WP2 - VISUALISATION DEMONSTRATION PROJECTS

A review of visualisation and virtual reality was conducted to identify technologies suitable for the display of a building’s 3D geometry and its associated data. The message from industry is to deliver targeted and cost effective solutions or they will not be adopted within the design process. As such the choice of software and hardware solutions is restrained by their capital and running costs. Having established suitable technology, two separate prototypes were developed to demonstrate and evaluate their appropriateness. Prototyping is a process by which users can be involved in testing design ideas using experimental, incomplete designs. Developing prototypes is an integral part of iterative user-centred design because it allows the developers to try out their ideas and to obtain feedback. Depending on the intended use there are different forms of prototypes. These range in complexity from screen mock-ups to fully functioning applications (Preece 1994). Although screen mock-ups are cheaper to produce in terms of time and money they are not appropriate for workplace evaluation by end users. Both prototypes were developed with sufficient functionality to allow the potential of the technology to be demonstrated and evaluated.

2.2.3  WP3 - USER REQUIREMENTS

A survey of user requirements was conducted using an online questionnaire and semi-structured interviews of the sponsors engineers. The methodology is discussed in Sections 3.0 & 4.0 of Paper 4 (Appendix D).

2.2.4  WP4 - EXTENSION OF VISUALISATION PRINCIPLES TO BUILDING PERFORMANCE DATA

An extensive literature review was conducted to establish which factors affect the successful representation of data. Having established prominent factors (Data, Tasks & Techniques) each was studied in turn. Each study focused on forming a single model which could be extended to building performance representation. The individual models were assembled to form the basis for a new visualisation framework.

2.2.5  WP5 - SOLUTION DEVELOPMENT, APPLICATION & TESTING

A final prototype was developed to show how the issues raised by the research could be addressed. This was accomplished by:

- Forming detailed lists of system requirements.
• Associating possible solutions with each requirement.
• Grouping similar requirements and solutions together.
• Iteratively implementing and adjusting the proposed solutions.

Evaluation comprised the use of heuristic guidelines and peer reviews during development, followed by field testing of the final software. Providing the software to users for evaluation within the sponsoring company and, in some cases, on live projects increased the relevance of the findings to the sponsor.

2.2.6 WP6 – DISSEMINATION

Dissemination of research findings was achieved through conference and journal publications. These were supported by a number of presentations given to the sponsors.

2.3 WORK PACKAGES

The work packages were conducted over a four year programme, as indicated in Figure 4 and detailed further in Section 3.0. Note that the bold numbers identify the relationship between the work package and the appended papers.

![Gantt chart of work packages]

Figure 4 - Gantt chart of work packages
The Application of Visualisation Techniques to the Process of Building Performance Analysis
3 RESEARCH TASKS

An overview of the research tasks undertaken for each work package follows. Further details of the tasks are presented in the appended papers, however it is recommend that these are not read in full until indicated in Section 4.0.

3.1 CURRENT PRACTICE REVIEW (WP1)

This can be sub-divided into two areas, the review of current building performance visualisation techniques and the review of current practice within the sponsors.

Techniques currently implemented within building performance analysis software were identified through a literature review. The review focused on the techniques used within commercial and academic thermal/energy analysis tools. To ensure that a broad selection of techniques were identified, a range of sources were used, including:

- Product literature (brochures, websites and white papers)
- Previous surveys/reviews and technical papers (journal/conference)
- First hand experience with demonstration software.

This combination was deemed appropriate as it provided a mixture of peer reviewed information and first hand experience.

Current practice, within the sponsoring company, was established by a critical evaluation of the visualisation techniques used by the engineers. This task was simplified as many of the current techniques were provided by the candidate whilst employed to develop and support the ROOM program. Over the two years that this position was held the following activities were undertaken:

- Technical Support – Supporting users on a daily basis ensured that the candidate was aware of common user errors and how current visualisation techniques made these hard for them discover.
- Program Maintenance – Program maintenance made it necessary for the candidate to isolate errors within complex algorithms by inspecting the results of test simulations. The candidate therefore regularly conducted detailed sensitivity analysis which pushed existing visualisation tools to their limits.
- Interface Development – A significant proportion of the tools used to visualise the analysis results were developed by the candidate.

The experience gained in this period provided a valuable understanding of the sponsor’s software and staff, which may not have been obtained by other methods. The observations and research carried out during this period were rationalised into three short case studies, presented in Paper 1 (Appendix A).

3.2 VISUALISATION DEMONSTRATION PROJECTS (WP2)

The simulation model used to describe a building consists of both numerical and geometrical components. The previous work package (WP1) established that the visualisation techniques used to interpret thermal analysis data are currently limited to static, often predetermined, tables and graphs. Therefore the geometrical component of the analytical data is not presented to the user. This work package identified, through a literature survey, the technology suitable for presenting 3D geometry. The survey focused on visualisation and virtual reality systems and their associated
software/hardware. As well as examining literature, trial versions of software were downloaded from appropriate websites and hardware vendors were visited. The review identified immersive and non-immersive 3D as the two most important system types to investigate. It also identified software suitable for producing both systems. Two pilot projects were therefore undertaken to produce separate demonstration prototypes using this software:

- The non-immersive prototype was developed sufficiently to allow user trials to be conducted within a controlled environment. This allowed measures of systems accuracy and efficiency to be made (see Paper 2, Appendix B).
- The immersive prototype was based on more complex software and hardware which restrict its development. The evaluation was therefore limited to observations made during demonstrations and feedback from the development process (see Paper 3, Appendix C).

The objective of this work package was to demonstrate and evaluate the technology identified as being suitable to display the building’s 3D geometry. A practical approach was adopted for several reasons. It allowed first hand experience of the technology, making it easier to identify potential problems and limitations. It also ensured the investigation was relevant to the sponsors’ data and the type of tasks carried out on it.

3.3 USER REQUIREMENTS (WP3)

In contrast to some engineering consultancies, thermal analysis software is used in the sponsoring company by a number of engineers spread throughout the company (approximately 40). As such there is no distinct analytical department but instead a continuously changing worldwide user base with varying degrees of training and experience. In order to understand the requirements of these users, and those in the wider industry, an online questionnaire was developed and distributed. The questionnaire was designed to be appropriate to all professionals who conducted some aspect of building performance analysis (not just thermal or energy). This ensured a wide range of opinions were gathered and facilitated a cross discipline analysis. Section 3.0 of Paper 4 (Appendix D) gives the rationale behind the choice of methodology and the resulting research tasks.

A significant number of responses obtained from the discipline-independent survey were from users of thermal analysis software. To further refine the information gained from these responses, six semi-structured follow-up interviews were conducted with the sponsor’s engineers. This allowed a finer level of detail to be obtained with a particular emphasis on the tools and practices used within the Sponsors. Section 4.0 of Paper 4 (Appendix D) gives further details on the choice of methodology and the resulting research tasks.

3.4 EXTENSION OF VISUALISATION PRINCIPLES TO BUILDING PERFORMANCE DATA (WP4)

Thus far, tools used for building performance analysis have been reviewed and their application within the workplace examined (WP1). Suitable Visualisation and VR technologies have been identified and applied through demonstration projects to the data produced by the sponsors analysis tool ROOM (WP2). These activities were complemented by a review of the use of building performance analysis tools within the construction industry and the sponsor’s company (WP3).
This work package (WP4) established, through an initial literature review, the importance of identifying the type of data being represented and the goal of the representation. Once these factors are identified, it is, in theory, possible to recommend a suitable visualisation technique. A subsequent, more extensive, literature review identified a number of different ways of classifying data, tasks (needed to achieve the goals) and visualisation techniques. These were synthesised into a number of separate theoretical models and extended/modified to be appropriate for building performance data. The review of data types produced a single holistic data model which was tested against the data produced by ROOM, see Section 4.4.1. The review of user tasks identified a set of tasks which formed the basis of questions used in the survey of the sponsor’s user requirements, see Section 4.4.2. Finally, the review of visualisation techniques established methods for encoding data and mapping the encodings to the model’s geometry, see Section 4.4.3. Combined, these [three] models form the basis of a framework designed to classify the factors important to the identification of suitable visualisation techniques.

3.5 SOLUTION DEVELOPMENT, APPLICATION & TESTING (WP5)

The ‘Extension of visualisation principles to building performance’ work package (WP4) produced a number of new theoretical models. Some of these were suitable for implementation whilst others require further research before application. The research proposals were formulated from the findings of Work Packages 1-4; the influences of these are clearly identified in Section 4.5. Five key system requirements were identified as necessary to support the interpretation of building performance data; these are presented alongside the associated proposals in Section 3.0 in Paper 5 (Appendix E). Each key requirement was implemented within one prototype so as to provide an integrated solution with a consistent appearance. The result of the development process was a fully functional prototype constructed from a number of different visualisation and interaction techniques. To complete the development within the allotted time period a number of Rapid Application Development (RAD) languages and 3rd party libraries/components were used. Whilst decreasing the development time, RAD languages often produce applications which execute more slowly than those developed in lower level languages such as C++. Note that a significant amount of effort was also required to improve the way in which ROOM exports its analytical data (from a comma separated file to a more suitable format); this had to be completed before the final prototype could be successfully evaluated.

Evaluation of the final prototype interface was considered an essential component of the research. A number of approaches were taken:

- **Heuristics Evaluation:** Throughout the software development process the prototype was evaluated against a number of existing guidelines.
- **Peer Review:** At important stages of the development the prototype was presented to supervisors and peers within the industrial and academic organisation.
- **Field Testing:** The final prototype was distributed to a number of users for tests on live project data. Feedback forms and usage monitoring provided rich information on the prototypes successes and failures.

The combination of heuristic evaluation and peer review ensured that the final interface was both usable and appropriate for infield testing.
3.6 DISSEMINATION (WP6)

The main research output consists of four peer reviewed papers, two of which were presented at international conferences and two published in international journals. A fifth draft paper has been produced to disseminate the details of the final prototype. This is intended for publication in the newly formed Information Visualisation journal (Palgrave) edited by Chaomei Chen. An additional summary of the research will be published in the Research Focus Journal. All papers and presentations are available to the sponsoring companies’ staff through the Intranet and a series of feedback talks commenced on the 20th August 2003. In addition the Final prototype is available for user testing thus allowing engineers to gain first hand experience of the research output.
4 RESEARCH RESULTS AND ANALYSIS

This Section presents the research undertaken to meet the aims and objectives stated in Section 2.0 following the tasks set out in Section 3.0. Where references are first made to the appended papers the reader is requested to read each paper in its entirety and then return to the discourse (these are underlined for clarity).

4.1 CURRENT PRACTICE (WP1)

A review of current building performance visualisation techniques revealed a heavy reliance on static two dimensional graphs and tables to represent nearly all numerical data. The majority of tools provide limited built-in post processing capabilities, instead opting to provide the ability to export the raw data ready for interpretation in spreadsheet packages. The only data presented alongside the building’s geometry in commercial packages were that associated with shading or comfort levels. These quantities are directly related to the geometry and are hard to represent without it. Non-commercial software showed a wider variety of techniques including; single page summaries of multiple analysis (Hensen & Clarke 2000), graphs arrayed across the screen according to multiple variables and multiple solutions (Papamichael 1997), detailed 3D surface plots of annual energy consumption (Milne et al 2001), interactive update of results whilst the user adjusted input in a media rich environment (Benkert 1996 and Braeske 1996) and the display of occupant comfort in an interactive 3D environment (Malkawi 1997).

Paper 1 (Appendix A) presents a review of current practice within the sponsoring company and examines the usefulness of dedicated post-processors and the customisation of spreadsheet packages. Note: each of the 3 example projects presented were produced by the Author shortly before commencing the EngD programme. Key findings include (Note the prefix ‘F’ denotes a finding and is identified as such so as to aid the structure of the document):

- F1 Spreadsheets support a limited number of graphical elements making it difficult, without additional development, to reproduce industry specific diagrams (pressure-enthalpy, psychrometric etc).
- F2 Spreadsheet based graphs are limited in the number of dimensions and the level of measurement available for each axis.
- F3 Spreadsheets do not, without additional development, support domain specific tasks such as locating an hour of the month or ‘plotting internal air temperature for the 3rd May’.
- F4 Interactive tools should attempt to support the seven tasks identified by Shneiderman (1998), display a reasonable amount of data whilst reducing clutter, clearly describe the data behaviour and be truthful.
- F5 Dedicated post-processors overcome many of the problems associated with spreadsheets but require significant development.
- F6 Spreadsheets may be successfully extended to support specific predetermined tasks or on a project by project basis to support adhoc tasks.
The review of current practice highlighted the benefits of software designed to support specific data representation tasks and how, at present, this is being developed on an adhoc basis. The following section examines the application of state-of-the-art technology to building performance thermal analysis data.

4.2 3D TECHNOLOGY PILOT INVESTIGATION (WP2)

The review of interactive 3D software and hardware identified two types of 3D applications; Immersive and Non-immersive (Desktop). Each type may be constructed using the same programming libraries or editing software and either may be suitable for distribution over a network (such as the internet). The key difference is the use of hardware to facilitate an immersive experience. Immersive 3D requires additional input and output hardware such as motion trackers and head mounted displays. The literature survey also identified a number of guidance documents, including those for: navigating non-immersive VR (Sayers et al 2000), the use of immersive VR for scientific visualisation (Dam et al 2000 and Baker & Wickens 1995), the usability of virtual environments (Gabbard & Hix 1997) and the design of 3D user interfaces (Bowman et al 2000). The following sections describe two projects carried out within the sponsoring company, for the purpose of this research, to establish the relative advantages of desktop and immersive 3D technology when applied to thermal analysis data interpretation (WP2).

4.2.1 PROJECT 1: INTERNET BASED 3D INTERFACE

In terms of technology this is the less ambitious of the two projects but the most extensive in terms of application and evaluation. The area of Desktop 3D technology chosen for investigation is known as Web3D and refers to the use of internet compatible standards and components to distribute 3D content to the users’ web browser. Web3D is particularly suitable for the display of simple 3D models and is therefore ideal for displaying the geometry of analysis models. The development tools are also inexpensive and there is little or no cost associated with the distribution of the media. In addition Web3D offers the potential to facilitate collaborative working with remote users. Further information on the potential of web based information visualisation is available in Rohrer and Swing (1997).

Paper 2 (Appendix B) reviews the use of the 3D interface in engineering design, discusses the application of Web3D and evaluates the performance of three different systems. This work clearly demonstrated that:

F7 It is possible to construct an interactive 3D interface based on analytical data using Web3D technology.

F8 That although standards exist for data transfer their implementation is prohibitively time consuming for use in prototype systems.

F9 Conducting in-house user trials produces data useful for steering the direction of future research but of insufficient fidelity to answer specific questions (i.e. which elements of the 3D interface hindered the user).

F10 3D interfaces have the potential to reduce both the amount of time taken and number of the errors produced by an engineer interpreting analytical results.

F11 The 3D environment requires careful design to support navigation and object selection.
Research Results and Analysis

The development of the prototype highlights a number of problems related to the association of analytical results to their underlying geometry. Datasets generated in the field of Computational Fluid Dynamics and Finite Element Analysis consist of large amounts of spatially located data. This is generally represented using iso-planes or surfaces (Keller & Keller 1993). In contrast thermal analysis datasets consist of a relatively small number of surfaces with a large quantity of temporal data associated with each. There is insufficient spatial data to colour code surfaces in more detail than a single colour per surface for a given hour. In this case multiple variables could be encoded using further properties such as texture or transparency but again this would be for a single time step. Therefore:

F12 There are a limited number of natural mappings between temporal data and single, often irregular, surface.

It is possible that moving to a more abstract representation of the building may maintain the users’ appreciation of the geometry whilst increasing the number of potential encodings. Abstract representation is discussed briefly in Pilgrim et al (2000) but not pursued further here.

4.2.2 PROJECT 2: AUGMENTED & VIRTUAL REALITY

The second project, an investigation of immersive 3D environments, relaxes the computing and cost based restraints applied to the first. The investigation focuses on the usefulness of various modes of interaction/navigation and looks at the implications of removing the desktop interface. The project was implemented with the aid of a 3rd party toolkit (ARToolkit) and the coding skills of a part time student employed by the sponsors. Paper 3 (Appendix C) gives full detail of the project. Key findings/lessons learnt are:

F13 The interaction between software and hardware is dependant on drivers which are often incompatible with other system components. This makes the system dependant on very specific hardware.

F14 The hardware is still expensive and many potential users did not have access to even the minimum requirements or funds to acquire them.

F15 Interaction in the VR mode was designed to allow forward and backward travel in the direction of the users view. This made it difficult to navigate around the exterior of the building (as the user had to repeatedly stop moving and turn to check their location).

F16 External inspection of the model using the AR mode was extremely intuitive, partially because all transformations centred on the current model. There is no natural mapping between the AR mode and internal views of the space.

F17 Colour coding surfaces according to input data was useful but suffered from the same limitations identified in Project 1 (See Section 4.2.1).

F18 Hiding surfaces according to input data proved useful for the reduction of unwanted data/geometry.

Although the technology had many drawbacks they were mainly associated with its implementation and not its ability to portray the desired 3D information. The lack of a two-dimensional (2D) interface whilst immersed means that more data must be
associated with the geometry or displayed as a layer on top of the geometry (possibly obscuring it). Therefore:

F19 It is necessary to combine 2D and 3D elements to present sufficient data alongside the geometry.

The design of a 2D interface for entering and displaying thermal analysis data was explored further in a project focused on the application of Personal Digital Assistants (PDAs). The project, described in Pilgrim et al (2002) and placed in context by Holmes and Pilgrim (2003), demonstrated that it is possible to usefully display thermal analysis input and output data within a limited screen area. To gain a better understanding of the type and quantity of data to be presented, and the purpose of that presentation, an investigation into user requirements was conducted.

4.3 USER REQUIREMENTS (WP3)

A survey of engineers was carried out to obtain information about a number of aspects of their use of simulation tools, and in particular: how frequently engineers use their simulation software, what data are involved in the process, what techniques are currently used to interpret the data and what skill levels does the engineer have. A two part process consisting of an online questionnaire and semi-structured follow-up interviews was used to gather information from simulation users, see Paper 4 (Appendix D). Further details on the questionnaire and its findings are also given in Pilgrim (2001). Note that the structure of the follow-up interviews was partly based on the tasks identified in Section 4.4.2 and the six user profiles produced from the interview responses are included in Section 4.0 of Appendix F. The key findings are:

F20 No two users have the same requirements for the display of building performance data.

F21 Users commonly employ aggregates like minimum, maximum and summation.

F22 Users prefer graphical displays to extensive statistics and often plot results against time or other results.

F23 Users are comfortable with 2D graphs and tables but happy to explore new techniques and technology.

F24 Users are not well trained and use the tools infrequently.

F25 Simulation almost always consists of multiple analysis runs many of which are conducted to validate the model and understand its sensitivity to certain input.

F26 Model validation means input data is as important to represent as the output.

F27 Not mapping the analytical data to the geometry reduces user satisfaction.

F28 The number of variables used is small, but multiple surfaces, time steps and runs makes the final dataset overwhelming.

F29 There is currently no mechanism to organise the analysis files (runs) or inspect changes across them.
Presentation to a 3rd party is more limited than expected. The most rigorous presentations occur at peer review with clients receiving short summary reports.

4.4 NEW VISUALISATION FRAMEWORK (WP4)

An initial review of visualisation literature was conducted to identify which factors affect the selection and implementation of visualisation techniques. The work of Mackinlay (1986a & b), Casner (1991) and Roth & Mattis (1990) was identified as most relevant to the research. Their work focuses on the design of systems that are capable of automatically producing an appropriate representation of data. These authors identify the data and task type as key to the selection of suitable techniques. It was therefore decided to review, in detail, three specific areas of visualisation; Data types, User tasks and [encoding] Techniques. Each of the three following sections (4.4.1, 4.4.2 & 4.4.3) reports the results of collating existing research and extending it in preparation for its application to building performance data.

4.4.1 DATA TYPE

An extensive review of existing data models led to the production of a new holistic model, elements of which were chosen for:

- their influence on the selection of visualisation techniques.
- how easily they are understood by potential users.

The main principle of the model is that of composite and atomic objects (Zhou 1996). An atomic object is a single piece of data and a composite object consists of one or more composite/atomic items. This allows data to be represented as a hierarchy of composite and atomic objects. An approach which has many similarities with the numerical and geometrical data associated with building performance analysis. The model is presented in Figure 5 and each of its attributes discussed in Section 1.0 of Appendix F. Of all the elements in the model, the measurement scale was identified as the most complicated to apply and therefore tested against ROOM output data (See Section 2.0 of Appendix F). Each item on the scale was easily identified within the data except for Ranks and Counted-fractions. These scales, alongside the rest of the model, will be relevant to other datasets as yet not examined.
Having identified the need to understand the type of data used in a visualisation the results of the user requirement survey (WP3) were revisited to establish which data is to be used in the visualisation. Analysis of the survey results identified a specific list of ‘data’ (temperature, humidity etc) and ‘related things’ (space, surface, time etc). Inspection of these lists revealed four main items of which the data relates to and a number of quantifiers by which it is measured, see Table 2. The bold headings identify the focus of the data and the first column (italics) identifies how this is quantified. For example “Hourly Space Energy Consumption” or “Maximum Surface Temperature”.

**Figure 5 - Proposed holistic data model**

<table>
<thead>
<tr>
<th>Domain</th>
<th>Geographical</th>
<th>Temperature</th>
<th>Mass</th>
<th>Temporal</th>
<th>Spatial</th>
<th>Spectral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Origin</td>
<td>Derived</td>
<td>Simulate</td>
<td>Measured</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Physical Type</th>
<th>Float</th>
<th>Byte</th>
<th>Integer</th>
<th>String</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Measurement Scale</th>
<th>Discrete</th>
<th>Binary</th>
<th>Names</th>
<th>Grades</th>
<th>Cyclic Grades</th>
<th>Ranks</th>
<th>Counted Fractions</th>
<th>Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous</td>
<td>Proportions</td>
<td>Percentages</td>
<td>Amounts</td>
<td>Balances</td>
<td>Cyclic Balances</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Composite Object</th>
<th>Distribution</th>
<th>Normal</th>
<th>Non-Normal</th>
<th>Bimodal</th>
<th>Skewed</th>
<th>Sparse</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. Components</td>
<td>Scalar</td>
<td>Vector</td>
<td>Tensor</td>
<td>Multivariate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Physical Type</td>
<td>Table/Record</td>
<td>Collection</td>
<td>Array</td>
<td>Structure</td>
<td>Object</td>
<td></td>
</tr>
<tr>
<td>Aggregation</td>
<td>Series</td>
<td>Group/Set</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graph</td>
<td>Network</td>
<td>Tree</td>
<td>Hierarchies</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mesh</td>
<td>Curvilinear</td>
<td>Irregular</td>
<td>Regular</td>
<td>Rectilinear</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### 4.4.2 User Tasks

A user normally adopts a number of analysis goals during the course of visual exploration of scientific data. Few attempts have been made to identify these goals and the underlying tasks. The most detailed classifications have been produced by researchers seeking the ability to automatically create informative graphics. For example Roth & Mattis (1990) state that one of the most important issues for graphical design is the role of the users’ goals in viewing the data. They go on to identify the following domain independent information seeking goals:

- Accurate value lookup.
- Comparison of values within, but not among different relations, which results in evaluation criteria favouring separate pictures rather than a single composite for several relations.
- Pair-wise or n-wise comparison of relations for the same data set.
- Distributions of values for a relation.
- Functional correlations among attributes.
- Indexing-needs for one or both data sets within a relation.

Casner’s (1991) general classification divides the users’ tasks into two types: Search and Computation. The problem solving steps that a user takes to complete a task without the benefit of information presentation are described as logical operators. These are replaced by perceptual operators which produce the same output (for the given input). These are identified as:

- Perceptual operators for search: Search, Search & lookup, Lookup and Verify.
- Perceptual operators for computation: Equal, Difference, Less than, Times, Greater than, Quotient, Plus.

Wehrend and Lewis (1990) state that Mackinlay, Roth and Mattis, and Casner all tackle the demanding problem of automating the selection of representation techniques, where it is required that all aspects of the visualisation problem be captured accurately. Instead they propose that a rough classification of techniques augmented by the human
users’ judgement may be adequate. For this Wehrend (1990) presents a large matrix correlating ‘objects’ and ‘operations’. These are:

- **Objects** - Scalar, Scalar field, nominal, direction, direction field, shape, position, structure and spatially extended region or object (SERO)
- **Operations** - Identify, Locate, Distinguish, Categorise, Cluster, Distribution, Rank, Compare, Associate, Correlate and Within and between regions.

This approach has been adopted by a number of researchers including Keller & Keller (1993) and Fujishiro et al (1997 and 2000). Fujishiro extended the list of Operations and combined the resulting taxonomy with Shneiderman’s (1986) Task by Type Taxonomy. The result was implemented in a system which proposed techniques, based on work by Wilkinson (1999), suitable for the tasks inputted by the user. The user is then guided in their selection of the most appropriate technique by supplementary empirical knowledge and domain examples.

Extending Wehrend’s matrix to include our data model is not feasible due to the complexity of that model and Fujishiro’s approach is, undesirably, limited to predefined information graphics. Instead it is proposed that the user be guided through the process of generating novel graphics based on rules which relate the data and tasks to appropriate visualisation techniques. A set of tasks and associated rules are therefore required. To do this the findings of Salisbury (2001) have been adopted. Salisbury proposes a set of tasks based on the those by Wehrend and supported by further user studies. He also presents guidance on how to identify the existence of each task, see Table 3.

**Table 3 - User Tasks as defined by Salisbury (2001)**

<table>
<thead>
<tr>
<th>Task</th>
<th>Indicators</th>
<th>Question (yes indicates presence)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial</td>
<td>Where, distribution, locate, region</td>
<td>Is spatial location important for at least one of the data sets?</td>
</tr>
<tr>
<td>Comparison</td>
<td>difference, gains, losses, from/to clauses</td>
<td>Are you interested in how the data values relate/compare to each other?</td>
</tr>
<tr>
<td>Optima</td>
<td>majority, minority, least, most, greatest, biggest, smallest</td>
<td>Are you looking for maxima or minima within the data?</td>
</tr>
<tr>
<td>Trends</td>
<td>What, from/to clauses, distribution, generally, movement, change, time period assessment</td>
<td>Are you interested in the way your data changes or behaves over a time period?</td>
</tr>
<tr>
<td>Relationships</td>
<td>What, How, from/to clauses, multiple data sets, depends</td>
<td>Are you interested in how some of the data sets relate to each other or affect the values of other data sets?</td>
</tr>
<tr>
<td>Aggregation</td>
<td>grouping based on data store field</td>
<td>Are you interested in classifications within some data sets?</td>
</tr>
<tr>
<td>Distinguishing</td>
<td>specific inclusion and exclusion clauses</td>
<td>Are you interested in individual data values within the data sets?</td>
</tr>
<tr>
<td>Calculations</td>
<td>sum, difference, total, average, median</td>
<td>Do you need to perform numerical calculations on data within or between data sets?</td>
</tr>
</tbody>
</table>

This table proved especially useful when surveying user requirements (see Section 4.3).
4.4.3 VISUALISATION TECHNIQUES

There are a large number and variety of visualisation techniques (Section 1.2.2). Whilst a number of these are likely to be appropriate to the building performance data, this is difficult to assess without understanding the principles by which they were constructed. Visualisation graphics are constructed by encoding the data and, in some cases, mapping the data to the underlying geometry. Both aspects are reviewed and extended as necessary.

4.4.3.1 Data encoding

In order to recommend techniques based on their relevance to tasks it is necessary to think of the construction of graphics in a structured fashion, where possible using validated guidelines. Table 4 summarises the attributes of information graphics identified through an extensive literature search.
### Table 4 - Properties of information graphics

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Values</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of graphic</strong></td>
<td>Geometric or Symbolic.</td>
<td>Geometric typically has several fields that are mapped to axis. Symbolic focuses on non-numeric data and displaying relationships (Grinstein &amp; Ward 2002)</td>
</tr>
<tr>
<td><strong>Common name</strong></td>
<td>Point/line/area/Bar chart, histogram, Scatter plot, Pie chart etc.</td>
<td>Various names used in Earnshaw &amp; Watson (1992), Keim (2001), Salisbury (2001), Yu (1995), Harris(1999) and Bounford &amp; Campbell (2000).</td>
</tr>
<tr>
<td><strong>Dimensionality of graphic</strong></td>
<td>0D $\rightarrow$ 4D</td>
<td>Earnshaw &amp; Watson (1992) describes dimensionality of primitive; Card &amp; Mackinlay (1997) identify the number of positional axis. Yu (1995) uses 1, 2 &amp; multidimensional.</td>
</tr>
<tr>
<td><strong>Type of axis</strong></td>
<td>Unstructured, Nominal, Ordinal or Quantitative.</td>
<td>Card et al (1999): The quantitative axis metric may generally be interval or ratio but also physical or geographical. Axes can be linear or radial.</td>
</tr>
<tr>
<td><strong>Primitive organisation</strong></td>
<td>Selective, Associative, Ordered or Quantitative.</td>
<td>Roberts (2000): Associative – belonging to category due to similarity, Selective – category formed by differentiating from others, Ordered – order of scale &amp; Quantitative – greater or less that comparisons.</td>
</tr>
<tr>
<td><strong>Primitive arity</strong></td>
<td>Single Variable (SV) and Multiple Variables (MV) marks Or Single Data (SD) and Multiple Data (MD) marks</td>
<td>A SV mark is associated with one variable, a MV mark is associated with several variables. A SD mark conveys a single value for a single data point, a MD mark shows a range of summary information regarding the local distribution of several data points (Senay &amp; Ignatius 1999b),</td>
</tr>
</tbody>
</table>
When constructing an information graphic the type of primitive and its attributes are of key importance to the users’ ability to perceive the required data. Note: the subject of perception is thoroughly examined in Green (1999) and Lohse (1997). Jacques Bertin is recognised as producing seminal work in the classification of graphical primitives [Implantations] and their attributes [retinal variables] (Bertin 1983). The main thrust of Bertin’s work is based on flat graphics, where the 3rd dimension is used to describe a primitive’s attributes, not a distance along the z-axis. Bertin suggests that, with up to three rows, a data table may be constructed as a single image by producing a scatter plot. He then gives an example of an XY Plot with the third attribute mapped to the points size. Bertin states that “An image has only three dimensions and this barrier is impassable” and then gives the solutions summarised in Table 5 for encoding a table containing four rows of data:

Table 5 - Bertins encoding of a four row table

<table>
<thead>
<tr>
<th>A series of 2x2 plots</th>
<th>2 plots with 3 Dimensions</th>
<th>Superimposition</th>
<th>Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
</tbody>
</table>

No mention is made of encoding the same point with both size and colour or of plotting a three dimensional scatter plot with points of different sizes representing the 4th variable, both of which are now recognised alternatives. Bertin also defined the primitives which could be implanted within a graphic:

- Points: A point in a plane is without surface area. A visible mark (which must have area) can nonetheless signify a point (without area).
- Lines: Theoretically without surface area but with length. In order to vary a line in texture, orientation or shape it is represented by a set of points.
- Areas: Occupies a fixed portion of the plane, to vary its size, texture etc. without changing its signification in the plane it is represented as a series of points or lines.

Noticeable is the absence of a 3D primitive such as volume. This has been addressed by several authors (Mackinlay 1986a, Card & Mackinlay 1997, Card et al 1999 and Roberts 2000) who suggest that Bertin’s classification should be updated to include volume and position on a third [z] axis. What appears to be missing within this work is a clear diagram of the extended primitives and their attributes, the closest being that by Roberts (2000), see Figure 6.
The figure does not clearly demonstrate, and was not meant to, the link between retinal variables and objects rendered in a three-dimensional environment. It is also unclear as to how some of the configurations would be rendered using modern computer graphics or indeed interpreted usefully by the user. The following alternative classification is proposed, Table 6.
### Table 6 - Data encoding

<table>
<thead>
<tr>
<th>Type</th>
<th>Point</th>
<th>Line</th>
<th>Surface</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>1 Pixel square</td>
<td>1 pixel diameter, various lengths &amp; shapes (1-3D) made of segments &amp; end points</td>
<td>1 pixel thick 2-3D shapes made of patches &amp; an outline</td>
<td>Enclosed 3D space made of voxels &amp; an outer surface</td>
</tr>
<tr>
<td>Position</td>
<td></td>
<td><img src="image1" alt="Line diagram" /></td>
<td><img src="image2" alt="Surface diagram" /></td>
<td><img src="image3" alt="Volume diagram" /></td>
</tr>
<tr>
<td>Orientation</td>
<td>N/a</td>
<td><img src="image4" alt="Line orientation diagram" /></td>
<td><img src="image5" alt="Surface orientation diagram" /></td>
<td><img src="image6" alt="Volume orientation diagram" /></td>
</tr>
<tr>
<td>Size</td>
<td>N/a</td>
<td><img src="image7" alt="Line size diagram" /></td>
<td><img src="image8" alt="Surface size diagram" /></td>
<td><img src="image9" alt="Volume size diagram" /></td>
</tr>
<tr>
<td>Colour</td>
<td><img src="image10" alt="Colour diagram" /></td>
<td><img src="image11" alt="Line colour diagram" /></td>
<td><img src="image12" alt="Surface colour diagram" /></td>
<td><img src="image13" alt="Volume colour diagram" /></td>
</tr>
<tr>
<td>Material Transparency</td>
<td><img src="image14" alt="Material transparency diagram" /></td>
<td><img src="image15" alt="Line material transparency diagram" /></td>
<td><img src="image16" alt="Surface material transparency diagram" /></td>
<td><img src="image17" alt="Volume material transparency diagram" /></td>
</tr>
<tr>
<td>Texture</td>
<td>N/a</td>
<td><img src="image18" alt="Line texture diagram" /></td>
<td><img src="image19" alt="Surface texture diagram" /></td>
<td><img src="image20" alt="Volume texture diagram" /></td>
</tr>
</tbody>
</table>

Key to the new classification is the inter-relationship between the primitives’ geometry. Here a point as well as being a visible mark (of a minimum size – typically one pixel) is also a placeholder for other primitives. Those primitives (lines, surfaces and volumes) consist of sub-primitives such as segments, patches and voxels placed at given points. Therefore to vary a primitives’ material (e.g. texture) different visual attributes are assigned to its sub-primitives. By allowing lines, surfaces and volumes to have arbitrary geometry, as well as representing primitives such as circles and spheres, the classification is applicable to scientific and information visualisation applications.
Key attributes are:

- Volume objects have been added as modern rendering techniques allow varying 3D colour, texture and transparency (Bajaj et al 1999 and Teschner 2000).
- All geometry (except points) can be positioned, sized or oriented in three dimensions. Note: If the primitive is symmetrical along any number of axes then rotation may not be perceivable in one or more of the axes.
- Points do not have geometry, size or orientation. This is achieved by placing a line, surface or volume at the points position.
- The material of each type of primitive, except points, may be varied along, across or throughout that primitive.
- Colour includes values of greyscale.
- Transparency has been added to the classification.

The position of a visible mark [on the spatial substrate] is one of the most effective ways of encoding data (Card et al 1999). It is therefore the primary consideration when creating new data representations. There are a number of positional techniques available to a designer as illustrated in Table 7.

Table 7 - Positional Techniques after Grinstein et al (2001) and Wong & Bergeron (1997)

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Example Techniques</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="image" alt="1D Cartesian, polar axis" /></td>
<td>1D Cartesian, polar axis</td>
</tr>
<tr>
<td>2</td>
<td><img src="image" alt="2D Cartesian or oblique co-ordinates" /></td>
<td>2D Cartesian or oblique co-ordinates</td>
</tr>
<tr>
<td>3</td>
<td><img src="image" alt="3D Cartesian, 2D triangular, Spherical, Cylindrical axis" /></td>
<td>3D Cartesian, 2D triangular, Spherical, Cylindrical axis.</td>
</tr>
<tr>
<td>3+</td>
<td><img src="image" alt="Radial (Spider/star), Parallel, Matrix of 1, 2 or 3D plots and N-dimensional Hyperbox" /></td>
<td>Radial (Spider/star), Parallel, Matrix of 1, 2 or 3D plots and N-dimensional Hyperbox.</td>
</tr>
</tbody>
</table>

These techniques, when combined with those for data encoding, offer a virtually limitless number of combinations for data representation. However if the encoding is to be based on the underlying models geometry then the positional techniques are less relevant.

4.4.3.2 Geometry mapping

There are two common approaches to mapping engineering analysis data into visualisations; these are (Shephard 1995):

- **Data sampling** – results data are sampled on a structured array of points using interpolation and/or extrapolation.
- **Conversion of results data to graphical primitives** – element types are matched to available graphical primitives (points, lines and polygons). 3D
elements such as hexahedra and tetrahedra can be decomposed by mapping the element faces to triangles and quadrilaterals.

The data produced by single zone analysis tools such as ROOM are generally related to either single surfaces or non-physical variables (e.g. room temperature). The data related to the zones surfaces may be converted to graphical primitives, in this case directly to polygons. However, this mapping restricts the amount of data which can be displayed on the polygon (see Surface column in Table 6 and Finding F12). Therefore, to facilitate the creation of richer information and scientific visualisations, a generic method for relating data to objects is presented. The technique is based on progressively/recursively sub-dividing, assembling or approximating volumes, surfaces, lines and points (see Figure 7). Each step in this process generates the possibility of mapping more data to the geometry:

- **Sub-division** results in additional objects and parameters on which to map variables. Each sub-object may then be treated independently.
- **Assembly** facilitates the grouping of sub-objects to form larger objects which may then be manipulated further.
- **Approximation** is the process of substituting an object with a lower order object, resulting in an approximate representation of the data and creating additional mapping parameters.
Figure 7 – A generic method for mapping data to geometry
The terminology and structure used in the figure are loosely based on Trott & Greasley (1999) and Treinish (1997). Note that the smallest unit is a point; wherever a point is placed (e.g. centre of surface) it is possible to substitute it for an alternative representation. Using this method it is possible to devise a variety of alternative mappings between the analytical data and the underlying geometry.

For example each surface of a thermal analysis model, which is a shell surrounding a volume, may be sub-divided into a number of strips. Each strip may be encoded using colour to represent different variables (i.e. one strip could represent temperature while another represents heat transfer temperature). Additional detail may be encoded by further sub-dividing the strips into patches to represent each time step of the variables. These patches (which are in fact surfaces) may then be substituted with [inner] lines that are rotated according to the time step and colour coded according to the variable at that time step. This example demonstrates the advantage of thinking about object decomposition, assembly and approximation.

Mapping data to 3D geometry will result in some data being hidden from the user as front surfaces may occlude back surfaces. The techniques in Table 8 are suggested as possible solutions to the problem of occlusion, note they may be combined as necessary.

**Table 8 - Solutions to surface occlusion**

<table>
<thead>
<tr>
<th>Linking (to other objects or labels)</th>
<th>Transparency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manipulation</td>
<td>Reflection</td>
</tr>
<tr>
<td>Animation (of object or viewpoint)</td>
<td>Multiple viewpoints</td>
</tr>
<tr>
<td>Unfolding</td>
<td>Exploding</td>
</tr>
<tr>
<td>Separating</td>
<td>Info-Shadows (surface data projected onto background)</td>
</tr>
<tr>
<td>Substitution (by other objects)</td>
<td>Shrinking</td>
</tr>
</tbody>
</table>

These techniques facilitate the display of data, encoded on surfaces, which may have otherwise been hidden from the viewer. The effectiveness of each technique is likely to depend on the overall complexity of the geometry and the purpose of the representation. If the primary purpose is to understand the geometry then separating the
surfaces is likely to be less effective than Multiple Viewpoints. Alternatively if the main purpose is accurate value look-up then laying the surfaces flat (Unfolding or Separating) may have advantages over the other solutions.

4.4.4 SUMMARY OF NEW VISUALISATION FRAMEWORK

The review of visualisation techniques and principles produced a number of findings and potential solutions:

F31 It is possible to construct a holistic data model which is relevant to building performance data (measurement level validated against ROOM data).

F32 There are a number of ways to classify user tasks; the work by Salisbury (2001) was the most appropriate to this research.

F33 A number of ways exist to encode data using primitives and their attributes; these have been extended in a new classification to include volume.

F34 Data may be encoded using position on a spatial substrate or mapped to the underlying geometry; a unique geometry mapping was proposed.

F35 Data displayed on 3D geometry may be occluded; possible solutions were identified.

Ideally the data and task models should be combined to enable the recommendation of optimum data encodings, positional techniques and geometry mappings. While this is a non-trivial challenge, it is believed that the fresh look at existing theory represents a step closer to the goal of automating the design of graphical representations. The output of this work package helped to inform the requirement-gathering stage (Sections 4.3) and formed the basis for the final prototype stage of the research (Section 4.5).

4.5 PROTOTYPE SYSTEM (WP5)

A final prototype has been developed to show how the potential solutions identified by the research can be implemented. The prototype comprises a user interface that has been designed to support a number of key tasks in an intuitive and interactive fashion. These tasks include: file management, gaining an overview of file content, single and multiple file results analysis and relating results to model geometry. Each task is supported by a combination of existing and novel techniques implemented within a single interface.

The users’ requirements (Section 4.3) were sufficiently diverse to require a number of separate techniques to visualise the data associated with the simulation. The following five views were proposed, see Table 9.

Table 9 - Proposed views and their purpose

<table>
<thead>
<tr>
<th>View (Tab name)</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>File</td>
<td>Manage the files associated with each project.</td>
</tr>
<tr>
<td>Overview</td>
<td>Identify the key differences in input data between multiple files.</td>
</tr>
<tr>
<td>Result Analysis</td>
<td>Identify key variables based on one month's daily/hourly values.</td>
</tr>
<tr>
<td>Result Comparison</td>
<td>Identify the key differences between output data stored in multiple files.</td>
</tr>
<tr>
<td>3D View</td>
<td>Associate numerical input and output data with each file geometry.</td>
</tr>
</tbody>
</table>
They were each implemented here on a single tab of a multiple tab dialog, illustrated alongside the proposed functions in Figure 8.

![Figure 8 - Prototype tabs and their proposed functions](image)

Each tab was designed to explicitly support one or more of the six tasks stated in Paper 4 (Appendix D, Section 5.0) and repeated in Table 10 alongside the associated tab.

**Table 10 - Prototype requirements and the associated view**

<table>
<thead>
<tr>
<th>The system should support the users to….</th>
<th>Dialog Tab name (View)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Check the input has been entered correctly (including geometry).</td>
<td>File, Overview, 3D View</td>
</tr>
<tr>
<td>Obtain an overview of the analytical input and output data.</td>
<td>File, Overview &amp; Result Analysis</td>
</tr>
<tr>
<td>Present both input and output at a peer review.</td>
<td>All tabs</td>
</tr>
<tr>
<td>Identify how output variables relate to each other and the input data.</td>
<td>Result Analysis &amp; Comparison</td>
</tr>
<tr>
<td>Understand the influences of changes to the models geometry.</td>
<td>3D View</td>
</tr>
<tr>
<td>Compare the results of multiple analyses.</td>
<td>Result Comparison</td>
</tr>
</tbody>
</table>

Each of these Tabs and their evaluation are discussed at length in Paper 5 (Appendix E). The influence of the research findings on the choice of solutions implemented within the prototype is summarised in Tables 11, 12 & 13.
Table 11 - Technology considerations

<table>
<thead>
<tr>
<th>Research Finding</th>
<th>Influence on Final Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spreadsheets are limited in their support of visualisation techniques and domain specific tasks (F1, F2 &amp; F3).</td>
<td>A standalone post-processor was therefore implemented.</td>
</tr>
<tr>
<td>Systems consisting of advanced hardware/software are costly and difficult to construct/maintain (F13 &amp; F14).</td>
<td>Additional hardware avoided. However new software development languages and toolkits were used.</td>
</tr>
<tr>
<td>Interactive tools should support the seven tasks identified by Shneiderman (1998), see Finding F4.</td>
<td>These were used during heuristic evaluation.</td>
</tr>
<tr>
<td>A 3D interface is capable of displaying the analytical geometry and some of the associated input/output data. However the number of mappings are limited making it necessary to link to 2D data representations (F12 &amp; F19).</td>
<td>The 3D View linked the geometry to a textual description of each surface and to a hierarchical view of the models elements.</td>
</tr>
<tr>
<td>Surface colour (F17) and visibility (F18) are useful for communicating surface values and properties.</td>
<td>A rule based system allows the user to map input and output variables to surface visibility and colour in the 3D View.</td>
</tr>
<tr>
<td>Industry defined data schema impose too many restrictions on prototype development, eXtensible Mark-up Language (XML) identified as possible solution (Paper 2, Section 5.4)</td>
<td>Industry standards not used, instead natural structure of data when combined with XML aided the rapid development of the prototype.</td>
</tr>
<tr>
<td>The AR/VR prototype displayed multiple analysis files (Paper 3, Section 4.0).</td>
<td>The prototype supports the user in importing multiple files; the 3D View displays each files geometry.</td>
</tr>
<tr>
<td>Navigation of both internal and external views of 3D models is difficult (F15 &amp; F16).</td>
<td>The 3D View fixes a rotation centre in the middle of the selected model. Transitions between models is animated to maintain user orientation.</td>
</tr>
</tbody>
</table>
### Table 12 – Visualisation techniques and principles considerations

<table>
<thead>
<tr>
<th>Research Finding</th>
<th>Influence on Final Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data can be modelled as atomic and composite objects (§4.4.1)</td>
<td>Overview tab considers the dataset as a composite object consisting of a number of composite sections. Comparing each atomic item in each section reveals differences between them.</td>
</tr>
<tr>
<td>Data from different domains has techniques associated with it (§4.4.1)</td>
<td>Temperature scales on the 3D tab use a heated-object scale (Rheingans, 1999 &amp; 2002).</td>
</tr>
<tr>
<td>Data maybe aggregated in different ways, this will affect the choice of technique (§4.4.1 &amp; F21)</td>
<td>The Result Comparison tab uses a classification of how the data is aggregated (object = Group/Set, Time = Series) to determine how it may be combined for plotting.</td>
</tr>
<tr>
<td>A table of key user tasks and the identifiers was located (§4.4.2).</td>
<td>These were used to aid user requirement gathering and for the heuristic evaluation.</td>
</tr>
<tr>
<td>Graphical primitives maybe encoded using their material attributes colour, texture and transparency (§4.4.3.1).</td>
<td>Colour and transparency (visibility) used in the 3D view. Texture not used due to concerns over readability and implementation constraints.</td>
</tr>
<tr>
<td>Geometry may be used as a framework for encoding data using the primitives’ attributes and relationships [Volume, Surface, Line &amp; Point] (§4.4.3.2).</td>
<td>3D View: Each model consists of a 3D volume, the shell of which was rendered using surfaces. Each surface has an outline and a number of triangular patches.</td>
</tr>
<tr>
<td>Surfaces may occlude each other (§4.4.3.2).</td>
<td>The 3D View allowed the user to manipulate the models position, orientation and transparency.</td>
</tr>
</tbody>
</table>

### Table 13 – User requirement considerations

<table>
<thead>
<tr>
<th>Research Finding</th>
<th>Influence on Final Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Users carryout multiple analysis for a single project (F25) but there is no mechanism to organise the files involved in the process (F29).</td>
<td>The File tab supports the collation of multiple files within a single project file.</td>
</tr>
<tr>
<td>Validation of the input data and the analytical results is a large part of the process (F25).</td>
<td>The Overview tab allows the intuitive comparison of the input data contained in multiple files.</td>
</tr>
<tr>
<td>Users of the thermal analysis tools are not extensively trained (F24) and are comfortable with 2D graphs and tables (F22 &amp; F23).</td>
<td>The techniques included within the prototype were kept simple (&amp; mainly graphical) to aid its acceptance by engineers. Instructions are also displayed on each tab.</td>
</tr>
<tr>
<td>Input and Output data is equally important (F26).</td>
<td>All analytical data included and represented together (not just output).</td>
</tr>
<tr>
<td>Users employ aggregates to simplify data (F21)</td>
<td>Data combined with min, max, average and sum on the Result Analysis and 3D View tabs.</td>
</tr>
<tr>
<td>Presentation to a third party not as important as originally thought (F30).</td>
<td>Presentation not explicitly supported by the prototype although recognised as needed in the long term.</td>
</tr>
</tbody>
</table>

---

6 The heated object scale follows the same scale as a black-body when heated, values for which were obtained from the internet (http://www.vendian.org/mncharity/dir3/blackbody/).
Evaluation of the prototype, by the engineers, was more limited than expected. This is due to the infrequent use of thermal analysis tools by individuals and their commitment to other aspects of design work. Based on limited use (total of 12 hours):

F36 The engineers rated the prototype as being in the range of slightly good to very good as a tool for visualising building performance data.

F37 The majority of engineers agreed that it improved the accuracy and efficiency of the data interpretation. This is corroborated by the discovery of several previously unknown errors within project data.

F38 All the proposed views, except that for organising files, were rated as slightly useful to very useful. The Files tab, rated as neutral, was used to coordinate multiple models, a function that was separately identified as useful.

F39 Although not used as much as the Overview and 3D View tabs, the Result Comparison tab was identified as one of the most useful and most likely to be used for the key tasks.

F40 The majority of problems identified in the prototype relate to coding errors, omissions, or the speed of command execution. These are systematic of prototypes in general and easily addressed.

F41 More subtle problems exist in the lighting of the 3D scene and the layout of multiple models for comparison. These, with a limited amount of investigation, should also be relatively easy to address.

In some respects the practical approach adopted to demonstrate the research solutions limited the type of techniques proposed to those immediately suitable for implementation and testing. In other respects this helped to avoid over complex techniques and aided focus on what the user actually required. As with all research projects of this nature, a number of problems were highlighted and will require further work. There are also a number of improvements which may enhance the prototype and the techniques it demonstrated. Three of these are presented here.

4.5.1 MULTIPLE CO-ORDINATED VIEWS

Whilst the prototype successfully demonstrated five separate views of the analytical data, their separation made them difficult to co-ordinate. For example, if the user selected two models on the 3D View tab they would then have to manually select the same models on the Overview and Result Comparison tabs. The separation also made side-by-side comparison difficult; therefore, any co-ordination is likely to be based on multiple views presented alongside each other (Chi et al 1998 and Stolte & Hanrahan 2000). The successful implementation of multiple co-ordinated views is likely to require significant changes to the present layout, the end result being a more condensed and possibly less intuitive interface. Therefore careful consideration is required as to how the views would be co-ordinated and what benefits it would bring.

4.5.2 WEATHER DATA

While the results [XML] file does contain some information on the external environment, much data is missing. The absent data is, at present, stored in a separate weather description file, tools for the interpretation of which exist. As this file has a significant impact on the predicted performance of a space it is desirable to incorporate
these tools within the package used to interpret the analytical data. By doing so, the engineer will have access to all data within an interface that supports its cross comparison, independent of its source.

4.5.3 **FORCE DIRECTED DIFFERENCE DIAGRAMS**

As discussed in Paper 5 the Force Directed Difference Diagram is a most significant research output. Whilst the process used to create the diagram is fairly simple, there are a large number of possible variations to it. Firstly, as discussed within Paper 5 (Appendix E), it may be desirable to allow the user to define the queries used to generate the unique sections. As the user is most aware of the variation of input data between files, they are possibly best placed to determine these sections. However, it is also conceivable that the process used to generate the diagram could be extended to automatically identify these sections. Whether manually or automatically determined, the sections may also be combined if files they represent are identical. For example, if File 1 consists of Sections A, B and C and File 2 consists of Sections A and C then there are two ways by which to represent it, see Figure 9.

![Standard Representation and With Grouped Sections](image)

**Figure 9 - The affect of grouping sections in difference diagrams**

The advantage of grouping sections in this manner is the reduction of clutter within complex diagrams. A further enhancement to the diagram comes in the form of weighting the connections (edges) between the sections (nodes). At present all edges have an equal weighting thus ensuring, where possible, symmetrical and compact diagrams. However, if it is possible to calculate a meaningful value for each edge then this would result in diagrams which encode more data. Sections which are not present within a file are currently weighted 0 and not displayed, all others are weighted 1. Instead of just detecting the presence of unique sections it may be possible to detect sections which have unique structure but different values. The difference between these values could be used to calculate some form of weighting which ranged from identical (1) towards extremely different (e.g. 10). Using this technique, files which contain sections with similar values will be positioned approximately the same distance from the section icon, see Figure 10.
Figure 10 - The affect of weighting connections in difference diagrams

The weighted sections version of the diagram indicates that the values represented by:

- Section A are similar in File 2 and 3 and not 1.
- Section B are smallest in File 1, a little bigger in File 2 & much larger in File 3.
- Section D are equal in all three files.

The diagram also demonstrates how it is possible to represent the difference diagrams in a table, which is similar from Bertin’s (1983) matrices. Further research is required to identify suitable weightings and identify whether this technique is indeed applicable to Bertin’s matrices.
5 CONCLUSIONS

Building performance simulation is a complex process during which the engineer is required to construct a detailed analytical model based on information from a number of disparate sources. There is often uncertainty both in the information and the manner in which it should be interpreted for model construction. Errors in entering the analytical model and interpreting the results of the simulation bring about a loss of accuracy. Improvements in the validation of the data entered and the representation of the simulation results will therefore increase accuracy and lead to better, more informed, designs. To validate a model, an engineer should check the input data, check the magnitude of important output parameters, look for erroneous output data and check the models sensitivity to various input parameters. This complex process leads to the construction of multiple, and often subtly different, models. To interpret the output data an engineer must identify important parameters or time periods and correctly read/calulate key values. In the context of validation this means that multiple models, parameters and time periods must be inspected and compared.

5.1 SUMMARY OF FINDINGS

This research has examined the building performance analysis process and determined:

- **The key tasks performed by engineers** – Simulation often results in multiple analysis runs to validate the model (F25) and there is currently no mechanism to support this process (F29). The results are often interpreted using aggregates and are presented more often to other engineers [at peer reviews] rather than to clients (F30). The primary purposes for using simulation are; plant sizing, predicting the likely internal environmental performance and confirming the design’s compliance with building regulations (Paper 4, Section 3.3.7). The six key simulation activities are identified in Table 10.

- **The data important to achieve the tasks** – The number of variables used is relatively small, but multiple surfaces and time steps make the final dataset overwhelming (F28). A holistic data model is presented in Figure 5 and partly applied to ROOM’s data in Section 2.0 of Appendix F. The data commonly used in thermal analysis are stated in Table 2.

- **The techniques used to achieve the tasks** – It is difficult to reproduce industry standard graphics using spreadsheet packages (F1) which are limited by the number of dimensions and level of measurement available for each axis (F2). Users prefer graphical displays to statistical analysis (F22) and whilst being comfortable with 2D graphs, they are happy to explore new techniques (F23). Spreadsheets do not support domain-specific tasks (F3) and are not capable of displaying the model’s geometry, this has been associated with reduced user satisfaction (F27). Due to these limitations spreadsheets are often extended (F6), or dedicated post processors are developed (F5).

These findings were combined with:

- **Two projects to evaluate visualisation technology** – It is possible to construct both a desktop 3D (F7) and immersive 3D interface for displaying building performance data. Three-dimensional interface have the potential to reduce both

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5 Note that the numbers preceded by an ‘F’ refer to findings reported in Section 4.
the number of errors made and the amount of time taken by an engineer interpreting the results (F10). There exist a limited number of natural mappings between the data and geometry (F12), of which colour (F17) and visibility (F18) were demonstrated. Three-dimensional interface require careful design to support navigation and object selection, navigation may differ depending on internal or external views (F15 & F16). The complexity (F13) and cost (F14) of hardware remains prohibitively high.

- **An investigation of visualisation principles/techniques** – The investigation established a new data model (F31), identified a relevant classification of tasks (F32) and developed techniques for: classifying data encoding methods (F33) and mapping data to geometry (F34). Several potential solutions to the problem of occlusion were also presented (F35).

The combination of these five sets of findings facilitated the formulation of a number of solutions to some of the problems/limitations identified within existing techniques. These solutions were implemented in a final prototype application and evaluated by nine engineers. Overall the prototype was rated as between slightly good to very good as a tool for presenting building performance data (F36) and the majority of the test engineers agreed that it improved the accuracy and efficiency of data interpretation (F37). Three-dimensional interfaces have the potential for navigating the building’s geometry but limitations for interpreting building performance data. The use of 3D was therefore limited to one of five views implemented within a final prototype application. Evaluation of these showed the 3D view to be the most popular in terms of time spent but not as useful as the Result Comparison view for achieving the main tasks (F39). Although not key to the majority of data interpretation tasks, the 3D view did seem to encourage a desire to present the analytical results. This prompted one of the engineers involved in the evaluation to state “Our work has often lacked the graphics that other disciplines, like structural engineers, have. The 3D [view] means we can start presenting at the same level for the first time”. The presentation aspect of the final prototype was purposely limited so as to focus on supporting the exploration of the data. This led many users to identify the prototype, in its present form, as a companion to spreadsheet packages. However, several engineers stated that if the prototype’s graphics could be customised for presentation then they would rather not duplicate them elsewhere. Building performance interpretation tools (such as the final prototype) must therefore explicitly support the creation of presentation graphics. For example user require the ability to customised items such as chart titles, legends and axis scales.

The implementation and evaluation of the research proposals within the final prototype produced a number of additional findings:

- The analysis of multiple models is made easier by organising their respective files into a single project file. This gives structure to a process which previously relied on convoluted file naming strategies.
- The validation process requires the relationship between multiple files to be understood. Force Directed Difference Diagrams are both appropriate and useful for this task.
- The display of input data is as important as output data. Building performance interpretation tools should support the representation of both.
- Interactively linked tables and charts offer are an intuitive and useful way of displaying multiple variables.
• Linking a table of summary values, based on aggregates of the users choice, with a table giving detailed values for a selected item is a suitable way to represent large time dependent datasets.

5.2 THE IMPACT ON THE SPONSOR

The research has identified visualisation techniques which, when applied to the sponsoring organisation’s thermal analysis data, show the potential to improve the accuracy and speed of its interpretation. In addition, the skills required to evaluate and improve these techniques have been developed and may now be applied to a number of software packages. Refined versions of a number of the techniques presented are likely to appear in future software. Innovation of this nature will lead to more consistent and improved design of thermal environments. Ultimately, this facilitates quality assurance and the ability to ‘get it right first time’. The research has demonstrated that investment in software interfaces, as opposed to analytical theory, is a worthwhile and rewarding process.

The first tangible implication of the research is demonstrated by the sponsor’s willingness to reconsider plans to transfer data between several software packages using a binary file. They are, on the grounds of this research, investigating XML as an alternative data transfer mechanism. This will allow the prototype and the techniques it demonstrates to be applied to future software.

5.3 THE IMPLICATIONS FOR WIDER INDUSTRY

Although a number of new techniques have been developed, the Force Directed Difference Diagram has the greatest number of potential applications. The diagram has been demonstrated within a building services application but is not domain specific. In fact it is relevant to any collection of datasets which have a hierarchical internal structure. The following steps are required for its application:
1. Convert the data files to XML.
2. Define sections using a series of XPATH queries.
3. Extract sections from XML files and compare to each other.
4. Produce an undirected graph from the details of each sections uniqueness
5. Render a graph using a force directed algorithm.

The final prototype is based on XML files and therefore skips the first step. It is also based on predefined XPATH queries; if this limitation was to be removed and an interface provided for the user to specify their own queries, then it would be applicable to all XML files with two or more unique nodes. Interfaces for constructing XPATH queries already exist but may require refining before being suitable for this particular application. Alternatively it may be possible to automatically detect unique sections, removing the need to define the section queries\(^8\). The only cost associated with this technique is the processing power required to generate the diagrams and the time taken to prepare the data. This makes it especially cost effective for applications that already produce XML files, which appears to be the current trend in mainstream applications.

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\(^8\) This may not always be desirable as automatically generated sections would differ between collections of datasets making the resulting diagram difficult to compare.
5.4  RECOMMENDATIONS FOR INDUSTRY/FURTHER RESEARCH

Users should be explicitly supported in the complex process of validating and using results produced by thermal analysis software. Specifically, they require tools to manage, interrogate and present the data associated with multiple models. Whilst the prototype illustrates the benefits of this approach there are a number of areas where enhancement is desirable. The prototype has two key functions, the management of the analytical process and the representation of analytical data.

5.4.1  MANAGEMENT OF THE ANALYTICAL PROCESS

At present the prototype currently works with ‘exported’ data, i.e. it reads XML files which are not the native file format of the analysis software. It is recommended that simulation packages use XML as their native input/output format. This would facilitate many enhancements, including:

- **Workflow integration** – Data is generally only exported at the users request, this additional step hinders the integration of a management/representation tool. Furthermore exported data can become ‘out-of-synch’ from the native files, leading to potential errors. Using XML as a native format will eradicate this.

- **Workflow management** – Management tools should be able to duplicate files and initiate the associated editors, thus moving towards a single tool for the management and interrogation of analytical data.

- **Model editing** – Eventually, the management tool would allow the user to identify key input data, modify that data and re-run the analysis without returning to the individual tools current used. The editing would either alter the original file or automatically duplicate it and edit the new file. This would lead to the reduction of input errors and rapid exploration of design alternatives.

- **Batch running** – Each of a number of parameters within the XML file may be altered systematically in a batch process, allowing for a number of solutions to be pre-computed. The interface will aid the interpretation of this large dataset.

- **Computational steering** – Ultimately, the process of altering a model, re-running the simulation and presenting the results may be possible in real-time. With an appropriate interface the user could steer the results towards target values by making subtle changes to input data (Mulder & Wijk, 1995) whilst monitoring a visualisation of the output data (Larkin et al 1997).

Industry should consider this approach to the exchange of data and the development of a management tools as key to reducing analytical errors and improving the value of design simulation.

5.4.2  REPRESENTATION OF ANALYTICAL DATA

Key to the management tools success is the successful representation of multiple analytical models and their associated data. This is clearly demonstrated by the research prototype presented. However, there remain a number of items that require further investigation prior to their commercialisation:

- **Quality Assurance Records**: The prototype offers a dynamic way to explore complex data, however on closing the application there is no permanent record of the steps taken. This is in contrast to the engineers’ use of Spreadsheets which generally results in separate worksheets for each step of the investigation.
These serve as a permanent record which may be stored for future reference. Research is therefore required into ways of producing such a record for interactive tools.

- **Force Directed Difference Diagrams**: This powerful technique requires further optimisation to include details such as: the key differences between sections, the order in which models were created/edited, the inheritance between models and the weighting of the connections (edges) between sections. Research into automatically sectioning files may also be useful to this and other industries.

- **Mapping variables to simple geometry**: Whilst only a limited number of techniques were identified it is possible that more abstract representations will allow a greater amount of data to be related to the models geometry. Alternatively research into linking 3D objects to two dimensional data displays may be required.

- **Surface occlusion**: Several techniques for overcoming surface occlusion problems have been identified. Research into the relative advantages of each is required.

- **Automatic presentation**: The automatic presentation of data has been the subject of a number of previous research efforts. The work presented here offers a number of new viewpoints on this subject area which could be the focus of further work.

### 5.5 CRITICAL EVALUATION OF THE RESEARCH

The research was conducted over a four year period during which many changes occurred. Most notably the researchers’ understanding of the subject matter improved allowing the project to become more clearly defined. As a result some of the initial effort had less impact on the final output than expected. The research is limited in a number of ways, the most prominent are:

- **Questionnaires, interviews and tests** – All survey and evaluation techniques used in the research required a large number of participants, primarily to ensure the results are statistically representative of the sampled population. Whilst every attempt was made to gain a good sample of software users, the specialist nature of the subject domain made this difficult.

- **Software users** – The engineers who use the software within the sponsoring company regularly change roles. This makes it difficult to maintain consistency during a four year research project. They are also influenced by their experience with existing software, internal politics and the projects they are currently working on.

- **Implementation** – Implementing a research idea requires a very high level of design. For example allowing users to define rules to hide surfaces (the idea) may be implemented in an almost infinite number of ways. It is therefore very difficult to isolate the implementation from the idea. If the implementation is bad or ‘quirky’ then testing is likely to indicate the idea itself is bad.

- **Applicability to other software** – Whilst it is likely that the findings are equally applicable to other single-zone thermal analysis software the research has been restricted to ROOM. The work presented did not include an evaluation of the techniques required to represent multi-zone models, however many of the ideas presented here are believed to be applicable. The main area of difficulty in extending this work to multi-zone models is likely to be related to the display of
geometry within the 3D View. As multiple zones overlap the techniques described in Table 8 will be required to avoid data being occluded from the user.

- **Existing Techniques** – Whilst every care was taken to identify the most suitable representation techniques there are undoubtedly a number of existing techniques which remain untried, and can be the subject of further research.

### 5.6 OVERALL CONCLUSIONS

It is possible to improve the interpretation of building performance data using existing visualisation techniques. Whilst a significant number of techniques exist their implementation alone is insufficient; instead, engineers require integrated tools which are both intuitive and easy to learn (in a short time period). Key to the successful selection and combination of visualisation techniques is a rigorous analysis of user requirements, an understanding of the subject domain and an in-depth knowledge of the techniques themselves. By combining theoretical research and practical investigation it has been possible to identify and evaluate suitable techniques. In particular the theoretical research helped to identify factors which affect the selection of the techniques whilst the practical investigation allowed these to be assessed in an engineering environment. By exploring the use of new technology early in the research programme it was possible to eliminate unnecessary or unsuitable techniques which may have otherwise distracted from the central purpose of the research. The final output, a working prototype and its evaluation, shows that it is possible to meet a number of diverse user requirements with a simple well designed application. In the case of building performance analysis this can be achieved with five different views of the data (file management, file overview, result analysis, result comparison and 3D presentation). Further development of these views and their ability to export graphics and data will lead to a powerful commercial application.

In conclusion the main contribution of the work is:

- The clear evaluation of engineering requirements.
- The practical investigation of three-dimensional techniques for the display of a buildings predicted thermal performance.
- A fresh look at the theory required to encode data based on it’s underlying geometrical model.
- The demonstration of an interface which, through careful design, facilitates the structured analysis of multiple datasets.
- The development of a new type of diagram which quickly confirms or refutes an engineers understanding of the design options analysed on a given project. The same Force Directed Difference Diagram has the potential to help the engineer identify incorrectly entered data and therefore has potential as a quality assurance tool.
6 REFERENCES


Elzas, M (2002), 'Maurice Elzas on Simulation Ethics', Crossroads, ACM Press, NY, USA, vol. 9, no. 2, pp. 3-6


Holmes, M. & Conner, P. (1991), 'Room a computer program to predict comfort at any point in a space', The proceedings of the CIBSE, Canterbury, UK.


Treinish, L. (1997), 'Scientific Data Models for Large-Scale Applications', Conference on Scientific and Technical Data Exchange and Integration, Maryland, USA.


Zeigler, B. (1976), Theory of Modelling and Simulation, Wiley and Sons, New York, USA.
APPENDIX A   PAPER 1

Full Reference:


Abstract:

Construction is by its nature a data-rich domain. It is also a competitive market with historically low profit margins. One step towards improving design efficiency is to develop techniques to examine and interpret construction related data. To achieve any significant improvement it is necessary to focus on a given sub-domain of engineering data. This paper focuses on analysis data, in particular building performance analysis data. This data, generated by performing an analysis of a building or its elements, may be used more efficiently and effectively by improving its visual representation. This is illustrated in this paper by three applications developed to improve the representation of specific building analysis datasets. Each exemplifies a structured and innovative approach to the development of applications used to enable engineers to dedicate more resources to understanding the results of their analyses.

Keywords:

Building, Thermal, Analysis, Weather, Monitoring, Spreadsheet, Data, Representation, Visualisation (Visualization)
1.0 INTRODUCTION

To successfully complete the design of a building and its constituent elements, engineers use numerous aids: design guides, manufacturers’ literature, rules of thumb and analysis tools. Of these, analytical tools generate the greatest amount of numerical data. A recent article by Laiserin (2001) states:

“Because the results [of the analysis] are so difficult to interpret from numerical answers alone, architects and engineers increasingly turn to visualisations. Whether in 2D or 3D, still images or animation, such visualisations play an increasingly important role in helping predict, identify, and correct potential trouble spots in building performance prior to construction”.

This highlights a requirement for engineers to have at their disposal the tools required to interpret analytical data. One such set of data is Building Performance Data; this falls into two categories: measured and predicted. Measured data can be viewed in real-time such as in Building Management Systems (BMS) and/or stored for later analysis such as in building monitoring. Building simulations also produce stored data suitable for further analysis. This paper focuses on the visual interpretation of examples of datasets used by building services engineers. These are; weather data (input to analysis), simulation results (output from analysis) and measured data (monitoring results). Why is this necessary? This question is answered eloquently by Wilde, Voorde and Augenboroe (1998), who state:

“The typical simulation tool produces a lot of output data. This data can be used to provide answers to design questions. However, without some sort of post-processing of the simulation output data, a simulation in itself does not answer the design questions for which the evaluation was invoked”.

The paper first presents an overview of normal working methods in this field followed by specific examples taken from everyday work in a consulting engineering practice.

2.0 CURRENT PRACTICE IN DATA REPRESENTATION

There is significant variation in the way in which engineers analyse and present building performance data. The analytical tools themselves typically provide the first level of interpretation, but when this becomes insufficient, additional tools are necessary. In a recent survey, only forty percent of users relied solely on their analytical package for the presentation of results. Instead, many engineers use spreadsheet packages. These general purpose processors are widely used for nearly all tasks involving some aspect of numerical data manipulation, formatting and presentation. Due to the breadth of their application, the graphical elements provided by a spreadsheet are often insufficient or inappropriate for the data being represented.
2.1 The Need to Support Specific Formats

The data used by engineers is often presented in a specific ‘industry standard’ format, examples are:

- Pressure-enthalpy diagram for refrigerants, axes: absolute pressure, enthalpy, temperature, specific volume, quality & entropy (CIBSE, 1).
- Psychrometric chart, axes: dry-bulb temperature, wet-bulb temperature, moisture content, specific volume, specific enthalpy, sensible/total heat ratio & percentage saturation (CIBSE, 2).
- Air flow & pressure drop chart, axes: pressure drop, volume flow rate, velocity, diameter (CIBSE, 3).

The Spreadsheet is usually the only tool available to the engineer to manipulate and plot data. As Spreadsheets support only a limited number of graphical elements, complex diagrams with irregular axes (those mentioned above, for example) are difficult if not impossible to reproduce. As a result it is often difficult to present data in its industry-standard form. Further limitations lie in the number of dimensions which may be plotted simultaneously and the format of the data (level of measurement). For example, a commonly used spreadsheet package is limited to plotting the following number of dimensions where continuous data are used:

- 2D - two continuous axes (xy Scatter plot).
- 3D - two discrete axes plus one continuous [z] axis (Surface plot).
- 3D - three continuous axes (Bubble plot) Note: no control over colour or shape means the 3rd dimension has limited applicability.

As a result it is often difficult to present the data in the most appropriate form. For example, plotting temperature measurements taken on an irregular floor grid would require three continuous axes.

2.2 The Need to Support Specific Tasks

Using a general purpose spreadsheet instead of a dedicated application can result in a large number of unnecessary tasks being performed. For example, if a spreadsheet is used to read a weather data file it is unaware of the file structure i.e. that each row of data is specific to a particular hour of the year (TMY2). Therefore, if the engineer requires the peak temperature for the middle of July, it is a laborious task to locate the appropriate row [data]. Although this is often a one-off task, there are several tasks that must be repeated on a regular basis. For example, on completing a thermal analysis the engineer might export the data to a spreadsheet to plot the building’s internal conditions (over a 24hr period). This is generally carried out after every analysis. This results in a significant amount of time being spent in manipulating data into an appropriate form.

Therefore, to improve current working practice and enable engineers to perform more efficiently and effectively, some improvements are required.

3.0 ENABLING ENGINEERS

There are many tasks that the engineer must perform which require tools and techniques to help improve their efficiency. These tools must focus on providing a means to easily represent data in a standard or appropriate form. The following
3.1 Weather Data Analysis

The weather data used to drive a detailed thermal analysis of a building generally consists of hourly values of around fifteen variables for a typical year. This equates to in excess of one hundred and thirty thousand values for a single year/location. Tasks performed on these data include:

- Calculating monthly averages of variables.
- Locating coincident monthly maximum and minimum values.
- Correlating variables to identify common coincident conditions (e.g. high solar radiation and high dry bulb temperatures).
- Locating trends/patterns in temperature and relative humidity.
- Gaining an overview of the data (i.e. is it a hot/cold or dry/wet year).

Each of the above tasks may be difficult to perform using a standard spreadsheet package. It is also clearly inefficient for each engineer to repeat the same tasks on the same data. As a result, standard forms of reporting weather data were developed and produced for each file available within the consultancy. This raised issues of deploying and maintaining up to date versions of the reports alongside the data files. It also introduced the necessity for the consultancy to maintain the ability to produce new and specific reports as further data were acquired. Since the reports were paper based, dynamic queries to identify specific correlations were not possible. In short, producing and printing static reports of electronic datasets removes the ability to obtain information not contained within the report template. The alternative is an electronic report which supports graphical user interaction with the underlying data. Shneiderman (1998) states that seven interactions should be supported by such an interface, and are summarised as:

- Overview: Gain an overview of the entire collection. An application should support an ‘overview plus detail’ also called ‘context plus focus’.
- Zoom: Zoom in on items of interest, preferably in one dimension at a time.
- Filter: Dynamic queries applied to the collection to remove uninteresting items.
- Details on demand: Browse the collection and obtain detail about a group or individual item.
- Relate: View relationships amongst items. Select an individual item and display other items from the collection which are related in some way.
- History: Keep a history of actions to support undo, replay and progressive refinement.
- Extract: Allow the user to extract groups of items or settings to be exported, saved, printed, etc.

This represents the ideal situation; in reality very few applications have successfully implemented all of them. The decision was therefore taken in our research to develop and distribute an application based on these interactions to support the stated tasks.

The development was based on the consultancy’s own FORTRAN libraries and routines for converting/calculating Psychrometric data. These were compiled into dynamic link libraries (DLLs) which could be accessed by a visual interface.
ability of the program to perform the stated task depends on its implementation. In this case the program may have been developed as an ‘add-on’ to a spreadsheet package or as a ‘standalone’ tool, Table 1 lists the merits of each.

### Table 1: Comparative merits of Standalone and Add-on Programs.

<table>
<thead>
<tr>
<th></th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spreadsheet add-on</strong></td>
<td>Familiar working environment. Built in ability to edit data. Integral plotting facilities.</td>
<td>Ensuring compatibility with existing and new versions of spreadsheet packages is resource intensive. Unable to plot standard engineering Psychrometric charts. Unable to import all weather files (e.g. binary).</td>
</tr>
<tr>
<td><strong>Standalone program</strong></td>
<td>May read all file types. Very simple interface. Can plot all required chart types. No compatibility issues.</td>
<td>File readers required for each file type. Additional code required for each chart type.</td>
</tr>
</tbody>
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The ability to plot all the required chart types, including Psychrometric plots, and to read numerous data files led to the decision to develop a standalone Weather Analysis Program (WAP), See Figure 1.

![Weather Analysis Program (WAP) interface screenshot.](image-url)

Figure 1: Weather Analysis Program (WAP) interface screenshot.
The development of a multiple document interface was carried out using Microsoft Visual Basic to include the following core functions:

1. Read, Edit & Save: Using a proprietary ActiveX component it is possible to read files, edit them in a spreadsheet environment and then save them in a common format.

2. Average, Minimum & Maximum: Calculation of monthly or daily values of a variable’s mean, maximum and minimum. Results displayed on spreadsheet component for copying/saving.

3. Statistics: Production of standard weather report including banded solar radiation and monthly degree days calculated using the DLLs mentioned above. The results are displayed on a spreadsheet component.

4. Correlation: Correlates two variables in user defined-bands, again the results are displayed on spreadsheet component.

5. Psychrometric Plot: Plots weather data on a standard Psychrometric chart (also known as a Mollier chart).

All of the above functions may be performed for a given range of months and for a given period during the day (e.g. April, 9am to 5pm).

The Psychrometric plot warrants further description. The decision to develop a standalone program was based on the inability to plot the required standard charts from a spreadsheet package. An example of these is the Psychrometric chart. Although dry bulb temperature and moisture content can be used to plot an XY Scatter plot (within a spreadsheet package) it is not possible to add the wet bulb [diagonal] and percentage saturation [curved] axes. Figure 2 illustrates a colour scatter plot of a year’s weather data on a Psychrometric chart within the WAPs.
Figure 2: Example Psychrometric plot in WAP.

The colour scale (light red, through red to black) used for each mark (in this case a point) indicates the number of occurrences of that condition. The colour of the point marker is used instead of size, as increasing the size of the marker in a scatter plot tends to obscure adjacent markers. The resulting plot facilitates a quick visual ‘Overview’ of the data allowing trends, patterns and outliers to be located. This figure also illustrates the Bounding Box, a facility used to specify a set of upper and lower criteria for temperature and percentage saturation. These criteria are then used to calculate the number of hours and percentage of the year within that range. The bounding box forms the basis for the ‘extract’ functions as described above. As before, it is possible to specify which time-periods are used (a ‘zoom’ function), including the ability to plot each month in a different colour. Also illustrated is the ability to obtain ‘details-on-demand’ for a specific point. This is achieved by displaying all physical properties related to a data point when it is selected using the cursor.

In summary, the requirement to display weather data in a clear and efficient manner was identified from deficiencies in current practice. This led to the development of a dedicated tool with a carefully targeted functionality. The tool was released to all engineers within the practice and is widely used to analyse weather files prior to their use with building simulation programs. The tool has since been modified to include the
ability to read and analyse the results of thermal simulations. This added functionality allows the engineers to easily display the building’s internal conditions on a Psychrometric chart, thus gaining a quick overview before performing further calculations. It also allows the engineer to ‘relate’ the input data (weather file) to the output data (simulation results) as an identical representation is used.

3.2 Understanding and Presenting Thermal Analysis Results

The process of analysing the thermal response of a building (or sub-space of that building) may be performed to different levels of complexity. As the analysis grows in complexity, the quantity of output data produced generally increases. At present, in-house software used for detailed thermal analysis produces in the region of twenty thousand data-points when used to analyse a single space for one calendar month. Data are output directly to a spreadsheet-compatible file. This has several advantages: all data are accessible, there is a familiar working environment, it facilitates further analysis and enables custom presentations. Although the data, once imported into a spreadsheet, does support basic graphical representation, it still remains difficult to navigate and time consuming to format correctly. It is therefore necessary to aid the engineer in both navigating, analysing and presenting the data. When presenting data, as well as supporting the seven types of interaction outlined above, it is important to:

- Display a reasonable amount whilst minimising clutter. Clutter may be reduced by removing unnecessary detail such as hatching and shading. Tufte (1983) introduced two numerical measures to quantify the amount of data encoded versus the area of the graphic or the ink used in the graphic. The data-density and data-to-ink ratios primarily encourage the elimination of unnecessary elements and the improved formatting of the non-erasable core.
- Describe behaviour. The primary function of information graphics should be to say something about the behaviour of the data, as emphasised by Tukey (1977):
  - “There cannot be too much emphasis on our need to see behaviour…. Graphs force us to note the unexpected; nothing could be more important”
- Be truthful. The variation in height, area or volume must directly relate to the variation in the numbers represented. Further, it must be clearly stated whether height, area or volume is being compared (Computer Graphics and Visualisation, 1993). The ‘lie’ factor is the ratio of the variation in visual effect to the variation in the data.

This must be carried out within a solution which supports the desired tasks, in this case these were:

- Formatting: produce standard tables.
- Graphing: Construct standard graphs, e.g. Air temperature Vs Time.
- Navigation: Move around the data (i.e. locate relevant tables).
- Comparison: Compare multiple data sets.
- Print: Print tables and graphs with standard headers and footers.
- Calculations: Calculate basic comfort indices based on the data.

As each of these tasks can be achieved within a spreadsheet, it was decided to develop an add-on utility to automate them (refer to Table 1 for further justification). The resulting utility is installed as a small menu bar within the host spreadsheet.
package. Each menu option displays a dialog related to one of the tasks above. For example, the format and graph options are shown in Figure 3.

These options allow the engineer to select any number of the eleven standard graphs to be produced automatically. Each of these graphs is based on the results of a single analysis. It is also common to compare the results of multiple analyses. This is facilitated by a similar dialog, extended to allow the user to select which files are to be compared. The comparison creates a table of values extracted from each dataset and a graph, see Figure 4.
The files and parameters to be compared are manually selected to ensure only relevant data are plotted. This minimises unwanted data (clutter). Thus the engineer can quickly identify the effects of input parameters as the data are clearly described (behaviour) in an appropriate form. This is a task that has traditionally been both time-consuming and error-prone.

3.3 Representing Building Monitoring Data

The previous examples have focused on the planned development of applications to enable engineers to perform common tasks. The final example shows how the same skill-set can be applied on a case by case basis to match the needs of individual engineers. In particular, it shows how to improve the manipulation of specific datasets and refine the way in which they are represented. This example is based on data produced by building monitoring devices such as temperature loggers. The monitored data obtained from spatially-located sensors typically consists of air temperature/humidity readings for multiple time steps. This poses a problem, namely, the combined representation of spatial and temporal data.

3.3.1 Spatial data

By adding spatial location information to the data points, the dimensionality of the dataset is increased. As previously stated, spreadsheet packages are limited in the number of dimensions they are capable of representing. Therefore, if we wish to present spatially located data within these packages, we must find ways to extend their functionality. For example there is no appropriate way to plot temperature measurements (T) taken at different locations (various X & Y distances in plan) within most common spreadsheet packages without making modifications (due to its limited number of axes). This is possible using the knowledge gained during the development of the add-on tools. For example, code written within the spreadsheets in-built development environment is capable of changing individual chart elements according to some data. So, in the example given, the data points X & Y values may be used to plot a reading’s position on an XY Scatter Plot and code used to alter the size and colour of each marker according to the data point’s value T. The resulting plot (Figure 5) is a Glyph Chart, a scatter plot with additional information encoded as a glyph for each data point (Computer Graphics and Visualisation, 1993).
The glyph is based on a mark that uses both colour and size to encode the same value (T). A mark is the most primitive component that can encode some useful information in any data visualization (Senay & Ignatius, 1996). There are four elementary types of marks; Points, Lines Areas and Volumes. It is desirable to use marks which allow automatic visual processing of the relationship between their properties and the underlying data. The properties of a mark that support pre-attentive processing are known as ‘retinal properties’ (after Bertin, 1963). Table 2 shows the relative effectiveness of seven retinal properties for Quantitative, Ordinal and Nominal data. The table aids the selection of graphical marks and their properties for the encoding of variables with different levels of measurement. Note: they are cross-separated according to whether the property is good for expressing the ‘extent’ of a scale or for ‘differentiating’ marks.

Table 2: Relative Effectiveness of Retinal Properties (based on data from Card, Mackinlay & Schneiderman 1999).

<table>
<thead>
<tr>
<th>Property</th>
<th>Quantitative</th>
<th>Ordinal</th>
<th>Nominal</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Extent</td>
</tr>
<tr>
<td>Size</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>Greyscale</td>
<td>Marginal</td>
<td>Good</td>
<td>Poor</td>
<td></td>
</tr>
<tr>
<td>Orientation</td>
<td>Marginal</td>
<td>Marginal</td>
<td>Good</td>
<td>Differential</td>
</tr>
<tr>
<td>Colour</td>
<td>Marginal</td>
<td>Marginal</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>Texture</td>
<td>Marginal</td>
<td>Marginal</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>Shape</td>
<td>Poor</td>
<td>Poor</td>
<td>Good</td>
<td></td>
</tr>
</tbody>
</table>
The marks in Figure 5 use two retinal properties (size and colour) to encode quantitative data (air temperature). The colour is used to rapidly differentiate marks whilst the size is used to gauge their extent (value). Double encoding variables may have the advantage of reinforcing their retinal qualities but can also lead the viewer to believe that more data is encoded than was intended (e.g. colour→temperature, size→humidity). Figure 5 also uses a background image to give the context of the readings and a scale to allow values to be determined. Both the scale and background image add to the fidelity of the resulting visualisation. The code required to do this can be written relatively quickly on a job by job basis as much of the code and ideas may be re-used from previous projects.

3.3.2 Temporal data

Data which is time dependent also introduces several challenges. Plotting even a single variable against time can be difficult if there are a large number of time steps. For example, plotting internal temperature for each hour in a given month (approximately 740 values) using a line graph will only highlight trends on a daily basis. Much of the hourly trends will be hidden due to the compressed time axis - see Figure 6 which shows temperature increasing towards the end of the month.

![Internal Temperature](image)

Figure 6: Hourly internal air temperature predicted for one month.

The time of day at which peak temperatures occur and whether or not this differs on a daily basis cannot be determined from this representation, i.e. the behaviour of the data is hidden at the hourly level. By re-using the code developed for the spatial data, it is possible to produce graphs which make more effective use of the plot area, See Figure 7.
This illustrates daily patterns previously invisible on the line graph by augmenting it with hourly values coded by colour. The figure also illustrates the problems of multiple axis plots, i.e. it is not immediately obvious which axis each data point is plotted against. This complexity can be removed using carefully designed interaction but remains for static [printed] graphics. It may also be argued that complex charts are only suitable for those trained in their use. Therefore they are not appropriate for static documents such as reports where the recipients’ abilities to interpret them are unknown.

4.0 CONCLUSIONS

The scope to improve the tools that engineers use to analyse and represent data specific to their profession has been highlighted. This is based on the need to reduce the number of repetitive tasks performed and present the data in a more appropriate and interactive form. By adding the ability to automatically perform standard tasks the engineer is then free to focus on the meaning of the data. This has been demonstrated through a series of example applications, each of which is presently in everyday use. The applications acceptance within the work place is partially based on their ability to support specific tasks, and partially because they operate within a framework (such as a spreadsheet) that is familiar to the engineer. The development of such tools is seen as key to improving the efficiency of design and constitutes best practice in building analysis data representation.
5.0 BIBLIOGRAPHY: VISUAL REPRESENTATION


6.0 ACKNOWLEDGEMENTS

The work detailed within this paper was carried out in partial fulfilment of the EPSRC Engineering Doctorate scheme at The Centre for Innovative Construction Engineering (CICE), Loughborough University. The Research Engineer, Matthew Pilgrim, is sponsored by Arup Research and Development where the work forms part of his responsibilities to provide appropriate tools to the firms’ engineers.

7.0 REFERENCES


CIBSE, 2: The Chartered Institution of Building Services Engineers Guide C, Reference Data, Fig C1.2, Page C1-4

CIBSE, 3: The Chartered Institution of Building Services Engineers Guide C, Reference Data, C4.2, Page C4-59


Computer Graphics and Visualisation, 1993: Visualisation 1: Graphical Communication, Courseware developed by The Manchester Visualization Centre for the ITTI Gravigs project.

APPENDIX B  PAPER 2

Full Reference:


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
1.0 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.

2.0 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 has been 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, Rad 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.

3.0 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.
The Application of Visualisation Techniques to the Process of Building Performance Analysis

- 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).

4.0 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.
5.0 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](image)

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.

6.0 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](image)

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.

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

![Usability Software - Rating based on a seven-point scale (Preece, 1994)](image)

8.0 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.
Table 1. User Trials – Accuracy and Rating Results

<table>
<thead>
<tr>
<th></th>
<th>Group 1</th>
<th></th>
<th>Group 2</th>
<th></th>
<th>Group 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Accuracy (%)</td>
<td>76.4</td>
<td>30.5</td>
<td>87.5</td>
<td>22.5</td>
<td>89.3</td>
<td>24.2</td>
</tr>
<tr>
<td>Rating (7 = Easy, 1 = Hard)</td>
<td>3.36</td>
<td>1.05</td>
<td>4.72</td>
<td>0.80</td>
<td>4.84</td>
<td>0.60</td>
</tr>
</tbody>
</table>

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 r² 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 r² 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.
9.0 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.

10.0 REFERENCES


Malkawi, A., (1997), Advisor to group project consisting: Ogun Arslan, Ruchi Choudhary and JoAnn Render, “Thermal Analysis in Design”, URL 4


Preece, J. (1994), Human-Computer Interaction, Addison-Wesley, Wokingham


URL 1, http://www.bartlett.ucl.ac.uk//web/Pangea/

URL 2, http://www.interoperability.com/


APPENDIX C  PAPER 3

Full Reference:


Abstract:

The development of a prototype mixed reality system for three-dimensional building form and data visualisation is presented. The requirements are:

- Allow user interaction with an external view of one or more buildings simultaneously.
- Maintain user contact with his or her normal working environment.
- Support multi-user input for collaborative design discussions.
- Facilitate intuitive navigation of the internal spaces.
- Present data relating to multiple design solutions.

The paper proposes that only by combining the relative advantages of the Augmented and Virtual Reality are these achievable. The overall goal is to successfully distribute amongst the workforce of an engineering consultancy an application that is accessible through inexpensive hardware whilst supporting more advanced input/output mechanisms. The guiding aim is to support the design process and facilitate communication amongst the project team and the construction client. The paper presents an overview of the system and highlights key issues raised during the development process.

Keywords:

Virtual Environment, Augmented Reality, Mixed Reality, Visualisation, Built Environment, Thermal Analysis and Building Performance.
1.0 Introduction

The system presented in this paper is designed to facilitate the validation, optimisation, review and presentation of building related engineering data using Mixed Reality (MR). MR seeks to combine the best features of real environments with those of virtual environments. Figure 1 illustrates the relative position of these in what Milgram et al [11] term ‘The Virtuality Continuum’. Each mode in the continuum is briefly described below.

![Virtuality Continuum by Milgram et al [11]]

1.1 Virtual environment

VR is a medium that provides participative 3D visualisation and simulation of virtual or computer-generated-worlds. Unlike animation (where previously created images are simply replayed in sequence) VR environments can be freely viewed and examined in any way from an infinite number of perspectives without noticeable delay - that is, in real time.

1.2 Augmented reality

Augmented Reality (AR) is a technology in which the user’s view of the real world is augmented with additional information generated by a computer [9]. It is complementary to Virtual Reality (VR) and enables users to interact with an integrated virtual and real world with ease. AR involves superimposing information in the form of a 3D computer-generated image on top of a ‘real-life’ visual scene. The scene may consist of still photographs and/or video images. It is possible, for example, to superimpose a 3D CAD model of a building onto a picture of its proposed site to show what the completed building will look like. In the case of video images, real time processing is essential to ensure currency of the information being relayed.

1.3 Augmented virtuality

This consists primarily of a completely computer-generated graphical display that has been augmented by the use of video ‘reality’ [11]. This involves superimposing a real scene on an aspect of a virtual reality model. An example could be integrating a video display of an outdoor scene with the view through a window in the VR model of a building. The key difference between this and AR being that, what is being augmented is primarily ‘virtual’ rather than ‘real’. In the future, however, it may be more difficult to make this distinction. The prototype described does not make use of this mode at present.
2.0 Virtual reality in design and construction

There has been considerable interest in the use of Virtual Reality in construction for the last decade although the uptake was slow at the outset [4] it is now gaining momentum. As a design tool VR has many advantages for the architect. By allowing architects to immerse themselves in their design, VR allows a much clearer understanding of both a qualitative and quantitative nature of the space they are designing. VR allows designers to evaluate proportion and scale using intuitive interactive modelling environments [10] and so simulate the effects of lighting, ventilation and acoustics in internal environments [12, 16]. As a visualisation tool VR is also used to communicate ideas from designers to clients by generating walkthrough models to test the design with the clients in a more direct manner [14]. VR can also be used to model the construction sequence in order to simulate and monitor site progress. This is done using a pre-prepared library of 3D graphical images of building components, facilities etc. and their related activities, and generate VR models representing views of the construction sequence at any given time of the process [1].

Mixed reality environments can be useful for site exploration, the visualisation of proposed buildings within the context of their locations, and the planning and monitoring of construction and refurbishment projects [2,13]. Data visualisation in this and other fields 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, Medicine, Social Sciences, and the Environment [7, 6, 8 & 15]. A comprehensive review of these systems is presented in the AGOCG technical report 9 [5].

3.0 System overview

The prototype described here is capable of importing geometry from a proprietary building analysis tool or a common 3D file format and displaying it and associated data in one of four ways:

- Desktop Virtual Environment (D-VE)
- Immersive Virtual Environment (I-VE)
- Desktop Augmented Reality (D-AR)
- Immersive Augmented Reality (I-AR)

The desktop mode requires a MS Windows driven PC and a web camera, Figures 2 & 3.

The Immersive mode requires a Head Mounted Display (HMD), a three-degree of freedom tracking device and a miniature video camera, Figures 4 & 5.

The Augmented Reality mode is based on recognising pre-registered patterns in real time from a video source. The patterns position and orientation is used to scale and rotate the 3D (virtual) object before it is rendered over the video source and displayed to either a standard SVGA monitor or a HMD, Figures 2 & 4.

The Virtual Environment mode uses the same rendering routines as the AR mode. Navigation of the virtual environment is either mouse driven or by a combination of
mouse commands and head tracking. The images are displayed on either a monitor or HMD, Figures 3 & 5.

In the following sections the software and hardware are discussed with respect to each of these modes.

Fig 2: AR desktop mode: Wire frame view
Fig 3: VR desktop mode: View of buildings interior

Fig 4: AR immersive mode: Multiple objects
Fig 5: VR immersive mode (hardware)

4.0 Augmented reality software

The pattern recognition software is available as a library of routines and example material called the ARToolkit developed at HIT Laboratory [3]. The rendering routines presently used within this toolkit rely on the GLUT libraries and as such are restricted to running under DOS. This restricts the development of applications running on Microsoft Windows operating systems, therefore the ARToolkit was converted to use OpenGL calls for the scene rendering and transformation. These converted files were then compiled into a basic application for displaying the captured video with a primitive
shape rendered in 3D over the recognised pattern. This application emulates the example provided with the original ARToolkit and demonstrates no more than an improved method of implementation.

Using OpenGL functions the frame rate of the video layer was significantly improved by rendering each frame as a texture (on a single polygon) thus maximising the use of the graphics cards dedicated texture memory. Again this technique has been observed elsewhere and is not novel. This improvement does, however, allow a full screen mode to be implemented; this is important, as it is not presently possible (without significant development) to render a single application window directly to a video output port. Instead the entire screen is replicated on the s-video port. Thus, to supply the appropriate images to the HMD it is necessary to have a full screen mode.

The ability to import three-dimensional models from two different sources has been implemented:

- ASE Files, this is a common file format that is available as an export from proprietary packages such as 3D Studio max.
- Analysis geometry, written within an in-house analysis tool containing additional data about the surface types (such as their properties).

To allow multiple models (of either type) to be presented simultaneously, a project file type was implemented. This contains information about the source of each model required within the project and the pattern with which it is to be associated. Further improvements of the AR code were:

- The ability to have a single model highlighted in the AR mode, thus allowing the transition into VR mode with the same model displayed. Models were selected from those available within the project file by looping through the list using the arrow keys. The selected model was identified using a red line around the base (Figure 4).
- The addition of an Auto-Scale feature to size the models to the pattern’s base area allowing models of varying sizes to be displayed side by side. This can be disabled if relative scales are required.
- A rotate mode was implemented to spin the selected model continuously thus allowing closer inspection.

5.0 Virtual reality software

The ARToolkit does not contain code for implementing desktop VR (referred to here as a Virtual Environment, VE). The HIT Laboratory has however demonstrated applications that combine AR with smooth transitions into a VE. Here, we use the routines developed to render the AR content to display the model in either a head-tracked or mouse-driven VE.

- The head-tracked Immersive Mode uses an InterSense InterTrax² tracking device to provide the user’s viewpoint orientation with regard to the model. This is combined with left and right mouse button commands to provide forward and backward flight along the line of sight.
- The Desktop Mode removes the necessity of owning a tracking device by allowing a standard mouse-driven cursor to govern the direction of movement.
Once in the VE mode it is possible to view any of the models within the project file from any viewpoint.

6.0 Desktop hardware

This is the most basic mode of implementation and is designed to allow the system to be used on relatively ‘low-end’ workstations with a minimum hardware requirement. The basic requirements are:

- A web camera (preferably USB)
- A standard personal computer

In this configuration the web camera is used to capture relatively low-resolution images in real-time. The software then augments these with the scaled and rotated rendering of the model on the monitor. In the Virtual Environment mode the camera is made redundant, the cursor is used to drive the onscreen rendering of the model. Due to the low resolution image captured from the camera, the AR Mode is limited to a sizeable window instead of full screen where the picture quality will be poor due to the amount of scaling required.

7.0 Immersive hardware

The Immersive Mode requires significantly more hardware and as such will not be appropriate for all users. The hardware used on the test system was:

- A graphics card with S-Video input and output, see below for further requirements.
- A miniature 12 volt colour S-Video quality camera.
- The Sony Glasstron HMD (S-Video or VGA input)
- The InterSense InterTrax² USB Tracking device designed to fit the Glasstron HMD

7.1 Graphics Cards

The system captures high-resolution images from the miniature camera through the S-Video input on the graphics card and supplies the AR or VR rendering back to the HMD through the output port. Several graphics cards were tested:

- Hercules 3D Prophet II GTS 64mb
- ASUS AGP-V7700
- ATI Radeon 64 VIVO

Of the three cards tested, no single card offered all the desired attributes, i.e. have both an input and output s-video port, be windows 2000 compliant and have video capture drivers compatible with the ARToolKit. One reason for this is that the newer cards, which are compliant with MS Windows 2000 (a more stable development environment), ship with video capture drivers based on Windows Driver Model (WDM). WDM is an attempt to make drivers more compatible but the ARToolKit was developed using Microsoft Vision SDK, which is based on the older Video For Windows (VFW) driver model. Therefore the project required a graphics card supplied with a VFW driver.
Another graphic card related problem is the control of the output to either the SVGA monitor or the s-video port. Ideally the image would be displayed on both simultaneously, thus allowing bystanders to see the immersive environment whilst the user is wearing the HMD. Not all graphics cards tested supported this mode of operation and none of them supplied any documentation relating to it. A software fix called TVTool was located which, depending on the architecture of the graphics board, allowed the output to be switched between the monitor and or the s-video port.

7.2 **Head tracking**

Head tracking is not required for the AR modes as video based pattern recognition is used; instead the head tracking is used in conjunction with a HMD to implement a more immersive VE experience. The first tracking device used was the Intertrax serial device designed to strap to the rear of the HMD. This device was bulky and required an external power supply. This was therefore changed for the newer Intertrax² device. The Intertrax² tracker, which is a lot smaller than its predecessor, is connected to the host computer via the USB port. The USB port supplies power to the device, thus removing the necessity for an external power source and it’s associated cable. The tracker data was captured using the API supplied with the device and used to orientate the user's view of the VE.

7.3 **Head mounted display**

The HMD used within the prototype had the following specification; low cost, high resolution (1.55 million pixels), lightweight and s-video/SVGA input. The image quality of the HMD was visibly greater when the images were supplied via a SVGA cable. This wasn’t possible because affordable graphics cards with dual monitor support (and a s-video input port) are not available and therefore a s-video supply was used.

7.4 **Video camera**

A mini CCD camera (33C-B36) with the following characteristics was selected:

- Size: 33mm (W) x 33mm (H) * 15mm (D)
- Weight: 280g
- Power source: 12v
- Output: 380TV lines via a BNC connector
- Interchangeable lenses (3.6 through to 12mm).

This was fixed to the front of the HMD using Velcro to allow its removal or repositioning. The camera output was converted to a standard s-video cable using an adapter and connected to the input port of the graphics card. Once the VFW drivers are correctly installed it is possible to test the cameras signal with a variety of video capture programs including Adobe Premier. The lens chosen for the camera greatly impacts the effectiveness of the AR experience. It is important that when the user looks through the HMD at the surrounding environment and for example his or her own hands that they see minimum distortion. For example the scale of their hands is correct, they are in focus and not distorted. The optimum lens for the hardware detailed here was found to have a focal length of 3.6mm. An amount of distortion was always present within the
system because of the use of a mono HMD, using two cameras and a stereo HMD was seen as prohibitively expensive.

8.0 Display capabilities

The system described so far is capable of displaying the contents of either an ASE or proprietary file as three-dimensional rendering. This is adequate to communicate the form of the object described by the file (e.g. a building) but not any additional data related to that object. Thus, several enhancements to facilitate data representation were made to the code. The data used relates to the input required for a proprietary thermal analysis tool. That is, in addition to the buildings’ geometry, it is necessary to supply each surface’s thermal properties and boundary conditions. Although the system described is limited to input data the same concept may be applied to the analysis results. The ability to display data in an intuitive way encourages communication between members of the design team leading to a greater understanding of the analysis. Several examples of analysis input representations are given.

8.1 Surface type

The analytical tools used in this study require the engineer to categorise the boundary conditions for each surface as Internal, External, Adiabatic or Isothermal. This data was mapped by applying colour to the surfaces (e.g. blue internal surfaces) to allow rapid identification of miss-classified surfaces. For large models containing many surfaces, a facility was added to allow surfaces of each category to be hidden from view. This allows the rapid identification of clusters of similarly classified surfaces.

8.2 Surface display

With all surfaces of the same category opaquely rendered in one colour, it became difficult to distinguish the edge of one surface from another in the same category. A wire frame mode was therefore implemented (figure 4). Both the wire frame and opaque mode could be independently turned on or off, thus allowing several different display combinations. With both modes turned on the surfaces are framed with a black outline allowing their edges to be distinguished. With just the wire frame mode turned on, the user is able to see through the model thus allowing them to appreciate its complexity.

8.3 Surface normals

Both the ASE and Proprietary files contained data relating to the normals of each surface. As it is common to check the direction a surface is facing it was considered important to represent this data within the application. For example, the proprietary analysis file requires all surfaces to face inwards. The surface normals were therefore rendered as a red line of fixed length from the centre of each surface. This representation could be extended to encode information such as the surfaces’ area, heat transfer coefficients etc by scaling the line’s length.
9.0 Application in engineering design

This project focuses on technological developments that may impact the way engineers design and collaborate within the context of large construction projects. Although the prototype is still in the early stages of development, the following scenarios have been identified, through discussions with the sponsoring company, as possible modes of operation.

9.1 Design validation & optimisation

An engineer may use the system to inspect and validate the design parameters associated with each surface of a building, both internally and externally, by switching seamlessly between the AR and VE modes. As the system’s capabilities mature and it becomes capable of displaying analytical results e.g. the building’s thermal response, optimisation of the design will be possible. For example, by assigning different input parameters and the associated analysis results to individual patterns within a single project file, multiple datasets/objects may be represented side-by-side in the immersive AR display mode (figure 4). By physically manipulating the patterns the engineer will be able to perform multiple comparisons of the data, thus facilitating the decisions required to optimise the design. Here, the immersive VE mode (Figure 5) is ideal for the in-depth exploration of both the three-dimensional model and the input/output of the analysis tool.

9.2 Collaborative design

In many scenarios it is necessary for more than one engineer to be involved in the validation and optimisation of the design. This collaboration is best supported by the prototype operating in the desktop mode where the camera or pattern can be easily moved by any engineer to emphasise his or her particular point of view on a design decision. The results of this movement are displayed in real-time, preferably on a large desktop monitor, figures 2 & 3. Likewise, it is possible for the engineers to work together around the monitor to navigate the design in the desktop VE mode. Remote collaboration may also be possible but has not been considered within this project.

9.3 Design review & presentation

Here, the prototype is used to facilitate ‘round-table’ discussions of the building’s form and associated analysis data. In this mode the miniature camera may be replaced by a tripod mounted digital video camera for improved image quality. This may also offer the ability to record the meeting (note the computer generated content would be missing but could be recorded from the system video output). The SVGA monitor used in the collaborative mode could also be replaced with a projection system, again allowing a higher level of detail to be seen by the participants of the meeting. In this mode of operation, the engineers could easily present and contrast several design options to the client. In addition to this, the intuitive AR interface will allow the client to manipulate the view of the model for themselves (previously not feasible with for unskilled operators). It will also be possible for a single engineer to walk through the interior of the model using the immersive VE mode whilst the other participants watch the projection screen.
10.0 Future work

The display of analysis results within the system could be implemented by reading separate result files and configuring a mapping variable e.g. mapping results column one to surface normal length. In addition, animated representations of data become feasible.

At present, the pattern matching routines require the entire pattern to be visible to the camera before the computer-generated image can be rendered. This, in practice, means the user must be careful not to obscure the camera view or to place anything (like a figure) on the pattern. Oblique angles can also reduce the routine’s ability to identify the pattern; this may be resolved by using several patterns with a known relationship mapped onto a solid (for example the numbers one to six on the sides of a cube). The system would augment the primary pattern (e.g. side one) even if obscured, by calculating its position from any of the secondary patterns (sides two to five) thus making the system more robust.

11.0 Conclusion

An augmented and virtual reality prototype for the presentation of a building’s form and its associated data have been presented. Several scenarios for its use have also been proposed. Both the development and application of the prototype have been driven by cost restraints common to the construction industry. At present this constraint may still restrict the use of HMDs, which remain equivalent in cost to a well specified personal computer. It is therefore proposed that an optimum system will support many different configurations of hardware, thus allowing companies to select the appropriate level of expenditure. The combination of AR and VR with immersive and desktop modes results in a flexible system suitable for many different engineering applications.

12.0 Acknowledgements

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13.0 References


The Application of Visualisation Techniques to the Process of Building Performance Analysis
APPENDIX D  PAPER 4

Full Reference:


Abstract:

Inadequate presentation of analytical results has been identified as a barrier to the use of simulation tools in the construction industry. The objective of this paper is to substantiate the existence of this barrier and to provide data to support research into its effective removal. The approach taken is to survey users by means of an online questionnaire and semi-structured interviews. Survey data is presented for each step of the analytical process alongside details of the respondents’ levels of experience with various software applications. The majority of respondents were either building services or structural engineers and an inter-group comparison is made. Building services engineers of various levels of experience participated in follow-up interviews and the results are presented. The survey results indicate that whilst difficulties of working with analytical results are recognised as a barrier to using simulation other barriers are perceived to be a greater hindrance. Users were also generally happy with the presentation of their results. However the interviewees all described the lengthy process required to validate their analytical models and stated that their tools require improvement to aid this process. The paper argues that whilst not recognised as the greatest barrier to the use of simulation tools there is justification for improving the manipulation and presentation of analytical results.

Keywords:

User, Survey, Questionnaire, Interview, Building Performance, Analysis, Simulation, Input, Output, Data, Results, Representation, Visualisation, Visualization.
1.0 Introduction

Building performance analysis, in the context of simulation, is the process of using a numerical model of a building and its systems to predict their likely performance, often to aid the choice of design solutions. The research presented here focuses on improving the way in which building performance analysis data is presented to the user. The process of presenting data to gain greater insight is known as visualisation (1). Appropriate visualisation is increasingly important in helping to predict, identify, and correct potential trouble spots in building performance prior to construction (2). In a recent research project (3) the time required to manipulate and present analysis data was identified as a significant barrier to the use of simulation. It is therefore reasonable to assume that the automatic representation of analytical results in a more appropriate, and easy to understand, form will improve the efficiency of the design process. To achieve this it is necessary to understand more about, not just the type of data being represented (4), but also other factors such as the given task, overall goal, and the presentation medium (5). It has been shown that successful visualisation is a result of the proper alignment of graphical format, research goal/task type, and the data types (6). To improve the representation of building performance data it is first necessary to understand how simulation tools are used and which graphical formats are suitable for the users. The paper presents the conclusions drawn from the results of a web based questionnaire targeted towards simulation users and the subsequent follow-up interviews with building services engineers.

2.0 Background

A brief overview of building simulation is presented followed by details of visualisation work related to analytical results.

2.1 Building simulation

In the past simulation tools were rarely used in building design process because they were both difficult and costly to use (7). The main purpose for which the output must be inspected is to answer the design question and validate the model (8). Often this requires the user to manipulate and represent large volumes of inter-related data. A process that is either carried out within the simulation program and/or additional ‘post-processing’ tools (E.g. spreadsheets). Both have problems associated with them:

- historically developers have focused on the input interface and calculation engine, relying on simple charts and tables to communicate the results (9,10);
- spreadsheets are widely used for tasks involving numerical data manipulation, formatting and presentation. Because of their general nature the graphical elements provided are often insufficient or inappropriate for the type of data being represented. Spreadsheets, without customisation, are unable to support specific tasks such as finding a particular hour in a year’s worth of data (11). What may be required are dedicated post processors.
2.2 Visualisation

Visualisation is defined by Card (1) as:

“The use of computer-based, interactive, visual representations of data to amplify cognition”.

Visualisation can be further divided into Scientific Visualisation and Information Visualisation. Scientific visualisation is applied to scientific data, and Information visualisation is applied to abstract data (1). Both are frequently used in conjunction with a collection of interaction and display technologies jointly known as Virtual Reality (VR). VR, as a medium, has three main properties (12):

- Interactive - users can interact with models;
- Spatial – models are represented in three spatial dimensions;
- Real-time – feedback from actions is without noticeable pause.

The task of achieving real-time interaction to complex simulation problems is found in almost every field where these tools exist. Pilgrim et al (13) highlighted the potential benefits of scientific visualisation for the representation of building performance. Post-processing is one of the most time consuming parts of the analysis process as results can contain values of multiple variables for typically 100,000 to 1 million grid nodes. The process of analysing these data can be made easier using visualisation techniques. In the case of fluid flow Kuhner and Krafcyzk (14) state that by visualising the simulation data together with the buildings’ geometry a better understanding of any correlation can be obtained.

2.3 Previous Surveys

Prior to surveying simulation users, a review of previous studies was conducted. Donn (15) presents a comparison between two surveys, one conducted in New Zealand (NZ) and the other on the west coast of the USA (US). The NZ survey was conducted in person and by telephone (80 valid responses) and the US survey by telephone and mail (44 valid responses). Both surveys targeted users of building environmental design tools. The NZ survey targeted a broad sample (i.e. all those involved in the process) while the US survey focused only on experienced users. The results indicate that the majority of simulation users:

- receive very little formal or informal training;
- use graphical analysis of results and very few use statistical analysis;
- plot variables against time;
- plot multiple results together;
- have worked with clients who need additional help in understanding the results of the simulation.

Donn concludes that it is essential to provide the users with tools that ensure the relationship between input data and the simulated building’s performance can be studied systematically. This paper extends that study to include a more detailed analysis of the simulation process, the barriers to its use and the levels of user satisfaction.

A survey by Ormerod and Aouad (16) based on a sample of 103 middle management professionals investigated the respondents’ perception of visualisation of
proposed building structures within their organisation. The sample consisted predominately of contractors and consultants of which the majority spent less than a quarter of their time creating or using visualisations. Coloured renderings and artist impressions were most commonly used for visualisation while computer animated images and VR were the least used. With the respondents limited experience of visualisation and VR it is surprising that they ranked these techniques as the most effective form of communication. This is possibly an indication of the attractiveness of this medium. Although the respondents ranked VR and animated images highly for their communication effectiveness they did not consider them appropriate to their organisation. Whilst Ormerod and Aouads’ study focused on the buildings form, the work presented here seeks to understand which media is commonly used by simulation users for visualising numerical results.

The objective of the survey presented here is to identify some of the barriers to the wide spread use of building performance analysis tools. The investigation comprised a web site based questionnaire followed by a task analysis comprising a limited number of semi-structured follow-up interviews. These are presented in turn.

3.0 Questionnaire

The questionnaire focuses on users who carryout thermal, energy and airflow analysis. It was therefore advertised through ‘The Chartered Institution of Building Services Engineers’ (CIBSE) and ‘The Royal Institute of British Architects’ (RIBA), the two most relevant professional organisations. The questionnaire homepage clearly stated that the questionnaire focused on the use of simulation and asked the visitor to respond only if they felt it appropriate. Due to the general nature of the questions the survey was also deemed applicable to other engineering disciplines. Therefore when advertised within the sponsoring company engineers from mechanical, electrical and structural disciplines were encouraged to complete the survey.

The decision to use a questionnaire implemented as a web site is based on the following rationale:

- questionnaires provide a more structured dataset than direct observation or interviews (17);
- the automatic collation of web based responses into a central database also makes the process easier to manage (18) and eliminates the requirement to travel to the subjects’ workplace;
- web based questionnaires also offer more control over format than Emails (19) and do not require the researcher to obtain contact details of possible respondents (as in mail and telephone questionnaires).

3.1 Design & Implementation

Guidelines for question design and layout are given in Oppenheim (17). Textual encoding is discussed in Weisberg and Bowen (20) and variable types/statistical techniques in Fleming and Nellis (21).
Exploratory interviews, as suggested by Oppenheim (17), were not carried out because the hypothesis had already been set by a previous work place study (13). Using the simulation process as a template the following key areas were identified and formed the individual sections of the questionnaire:

- General details - Information about the user;
- Input Data - Information about the process used to build the simulation model;
- Analysis - Details of the steps taken to perform an analysis;
- Output Data: How the users interpret the analysis results.

A three phase pilot study was carried out to ensure the clarity and relevance of the questionnaire:

- Phase 1: The questionnaire was designed and then discussed by the research team, leading to minor changes;
- Phase 2: The questionnaire was implemented within the sponsoring organisation where 35 responses were gained;
- Phase 3: The results of Phase 2 were reviewed by the authors and several modifications made to the questionnaire’s format and content.

The responses obtained during the piloting of the questionnaire were used solely to improve its’ design and are not included with those presented in the following sections. The final design included four types of questions; free text, multiple selection of specific categories, single selection of specific categories and finally selection of a point on a Likert scale (See example in Figure 1).

![Figure 1 - Example Question](image)

The questionnaire was implemented on a web site consisting of: a welcome page, four pages of questions (key areas as previously identified), a general questions page, a results overview and separate pages for each section of results. The users’ responses were stored in a database which was subsequently used to automatically generate summaries of the results. Access to the summaries was given to those who had completed all sections of the questionnaire. It is believed that this served as an incentive to both visit the site and answer the questions. A general questions page was used to gather the opinions of any non-users that visited the site, results of which are not presented here.

### 3.2 Questionnaire Analysis

After two months online, the questionnaire was closed and responses collated from the central database. As several respondents opted not to complete all sections of the survey, some results were missing. The final response rates were:
The Application of Visualisation Techniques to the Process of Building Performance Analysis

- Section 1, Input Data: 87 People;
- Section 2, Analysis: 79 People;
- Section 3, Output Data: 63 People;
- Section 4, General Information: 62 People.

The questionnaire is based on an open sample and as such the results cannot be proven to be representative of any given population, but with sufficient responses patterns can be identified and cross-discipline analysis is possible. The responses to the open-ended questions were encoded using the manifest technique i.e. based on the substance of the response not the style. The contextual approach was used to develop the manifest codes (20). This involves spending time reading a portion of the answers looking for common keywords or categories used in the respondents answer.

The majority of data collected by this survey is categorical (including the encoded text). As the measure is not continuous the number of valid statistical techniques is limited. Rank order data is only suitable for the use of distribution-free (non-parametric) techniques. Spearmans rank-correlation (rs) formally tests whether the relationship between two related variables is monotonic (i.e. if the y scores are consistently increasing or decreasing with increases in the x scores). Values of rs can be interpreted as from -1 perfect negative correlation to +1 for perfect positive correlation. Histograms were used to identify any patterns amongst single variables and graphical cross-analysis was combined with Spearmans coefficient to identify any relationship between variables.

3.3 Questionnaire Findings

The responses were almost evenly split between HVAC engineers (46%) and structural engineers (40%) allowing comparisons between the two disciplines. The results from the remaining 14% of respondents (electrical, mechanical, acoustics engineers or architects) were discarded for the following analysis.

3.3.1 Barriers to Simulation

Nearly all respondents (80%) felt there were barriers to the use of simulation. The most commonly identified barrier was the lack of training/knowledge and the low perceived value, principally by the client, of simulation, Table 1.

Table 1 - Encoded responses to “Do you consider there to be barriers to the widespread use of simulation. If so what are they?”

<table>
<thead>
<tr>
<th>% of Respondents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lack of training and knowledge</td>
</tr>
<tr>
<td>Value to client and cost of simulation</td>
</tr>
<tr>
<td>Tool: selection, complexity, availability &amp; limitations</td>
</tr>
<tr>
<td>Obtaining input in a suitable form and level of detail</td>
</tr>
<tr>
<td>Time required too long</td>
</tr>
<tr>
<td>Results: confidence, accuracy &amp; understanding</td>
</tr>
<tr>
<td>Data: exchange &amp; consistency problems</td>
</tr>
<tr>
<td>Yes: Other</td>
</tr>
<tr>
<td>NO</td>
</tr>
</tbody>
</table>
NOTE: Where the subject could give more than one response the tables indicate the ‘% of respondents’ that gave that particular response. Where the subject could only give a single response the tables indicate the ‘% of total responses’.

3.3.2 Training

This is not surprising when considering approximately 70% of respondents are self taught users of simulation, Table 2.

Table 2 - Responses to “Which method of training do you commonly use for analytical software?”

<table>
<thead>
<tr>
<th>% of Total Responses</th>
<th>Teach yourself using program documentation etc</th>
<th>Taught or helped by a colleague</th>
<th>Attending internal training courses</th>
<th>Attending external training courses</th>
<th>None of the above are applicable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>69.4</td>
<td>21.0</td>
<td>0.0</td>
<td>3.2</td>
</tr>
</tbody>
</table>

3.3.3 Levels of Satisfaction

Levels of user satisfaction are presented in Table 3, the differences between structural and HVAC engineers responses are explored in the subsequent cross analysis with other questions.

Table 3 – Grouped response to “With reference to your main analysis tool, how satisfied are you with the presentation of the results?”

<table>
<thead>
<tr>
<th>% of Total Responses</th>
<th>Very or Slightly Satisfied</th>
<th>Neutral, Slightly or Very Dissatisfied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>66.0</td>
<td>34.0</td>
</tr>
<tr>
<td>Structural</td>
<td>87.5</td>
<td>12.5</td>
</tr>
<tr>
<td>HVAC</td>
<td>50.0</td>
<td>50.0</td>
</tr>
</tbody>
</table>

3.3.4 Frequency of Use

The frequency of using simulation tools varies from daily to only several times a year, Table 4.

Table 4 – Response to “How often do you use simulation?”

<table>
<thead>
<tr>
<th>% of Total Responses</th>
<th>Daily</th>
<th>More than once a week</th>
<th>More than once a month</th>
<th>Several time a year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>16.1</td>
<td>29.9</td>
<td>33.3</td>
<td>20.7</td>
</tr>
</tbody>
</table>
The majority of respondents who used the tool more than once a week were satisfied with the presentation of the results. Conversely the respondents that use the tool less than once a week were generally more dissatisfied with the way the results are presented, Figure 2.

One possible reason for higher levels of dissatisfaction in infrequent users is the time that is required to relearn and become comfortable with complex interfaces. There is a weak positive correlation ($rs = 0.42$) between levels of satisfaction and increased frequency of use for HVAC engineers but a very weak negative correlation for structural engineers ($rs = -0.21$). This may be due to a difference in the complexity/quality software being used by each discipline but no evidence was located to support this.

### 3.3.5 Input & Output Data

More than 80% of analysis tools require 3D geometrical input, most of which (67%) is manually entered into the simulation tool. While manually entering the data the user gains explicit knowledge of the geometry whilst also making any necessary simplifications (e.g. removing unnecessary detail). On examining which type of tool is used for representing the output data it should be noted that 25% rely solely on post processors with the rest choosing to use either the simulation tool alone or in conjunction with a post processor. No statistical correlation is evident between the type of tool used and the level of satisfaction reported, Figure 3.

However the results suggest that those using post processing only form 52.9% of the respondents reporting neutral attitude or some dissatisfaction, but only 11.1% of those who report some satisfaction with their tool. Conversely of those using the simulation package, with or without a post processor, 47.1% report neutral attitude or some dissatisfaction and 88.9% report a degree of satisfaction.
3.3.6 Quantity of Data

Sixty percent of respondents perform more than ten analysis runs per simulation, with each run resulting in approximately 1,000 to 10,000 data points. Structural engineers generally perform more analytical runs than HVAC engineers, with structural runs perceived as producing more data than HVAC runs. There is no correlation between the amount of data produced by the simulation and levels of satisfaction with its representation, but there is a weak positive correlation between the number of runs performed and increasing dissatisfaction (HVAC rs=0.34, Structural rs=0.3). This may be because existing tools do not specifically support the comparison of multiple runs.

Important Data

Respondents were also asked which variables were most important to understand/present and most difficult to present. HVAC respondents (Table 5A) considered air temperature as the most important variable to understand and present, it was also identified as one of the four variables stated as most difficult to present. The second most important variables to present are energy and load related, these are rated as easy to present. Surface temperatures and heat flow variables are important to understand but not present. Whereas comfort and air flow data are equally important to present but difficult to do so. Structural respondents (Table 5b) considered force, deflection and bending moment related variables as most important to understand and present. All variables are considered more difficult to present than element attributes.

Table 5 - Percentage of respondents that identified each variable when asked “Which parameters do you see as A) most important to your understanding of the analysis? B) most important for the presentation of the analysis results? C) most difficult to present?”
5A) HVAC Engineers

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A: Important to understand</th>
<th>B: Important to Present</th>
<th>C: Difficult to present</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Temperature</td>
<td>54.5%</td>
<td>50.0%</td>
<td>18.2%</td>
</tr>
<tr>
<td>Surface Temperature</td>
<td>13.6%</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Heat flow</td>
<td>22.7%</td>
<td>0.0%</td>
<td>13.6%</td>
</tr>
<tr>
<td>Comfort</td>
<td>4.5%</td>
<td>18.2%</td>
<td>27.3%</td>
</tr>
<tr>
<td>Energy &amp; load</td>
<td>18.2%</td>
<td>36.4%</td>
<td>4.5%</td>
</tr>
<tr>
<td>Air flow</td>
<td>4.5%</td>
<td>18.2%</td>
<td>22.7%</td>
</tr>
<tr>
<td>Solar data</td>
<td>4.5%</td>
<td>0.0%</td>
<td>4.5%</td>
</tr>
<tr>
<td>Moisture</td>
<td>9.1%</td>
<td>4.5%</td>
<td>4.5%</td>
</tr>
</tbody>
</table>

5B) Structural Engineers

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A: Important to understand</th>
<th>B: Important to Present</th>
<th>C: Difficult to present</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forces</td>
<td>43.5%</td>
<td>43.5%</td>
<td>21.7%</td>
</tr>
<tr>
<td>Bend Moments</td>
<td>30.4%</td>
<td>21.7%</td>
<td>17.4%</td>
</tr>
<tr>
<td>Deflections</td>
<td>43.5%</td>
<td>47.8%</td>
<td>17.4%</td>
</tr>
<tr>
<td>Element Attributes</td>
<td>0.0%</td>
<td>8.7%</td>
<td>8.7%</td>
</tr>
<tr>
<td>Dynamics &amp; Kinematics</td>
<td>8.7%</td>
<td>13.0%</td>
<td>17.4%</td>
</tr>
<tr>
<td>Other</td>
<td>26.1%</td>
<td>26.1%</td>
<td>39.1%</td>
</tr>
</tbody>
</table>

Presentation Format

Tables and graphs are most commonly used to present output data however respondents believed that 3D graphs and VR have the most potential to improve its representation. Figure 4 compares the responses to two questions:

- What format/media do you currently use when working with your output data? [multiple selections possible]
- Which one do you believe has the potential to enhance the visualisation of your building performance analysis results?

The figure illustrates the potential for a shift away from existing techniques towards 3D Graphs, VR and Animation. One possible application of VR is the interactive display of analytical results on or linked to the model’s geometry.
The survey shows that a greater percentage of respondents who reported dissatisfaction with the presentation of their results used tools which did not map the data onto the original geometry, Table 6.

Table 6 - Encoded responses to the question "Does your present use of visualisation include the mapping of variables onto the original geometry?"

<table>
<thead>
<tr>
<th></th>
<th>Very or Slightly Satisfied</th>
<th>Neutral, Slightly or Very Dissatisfied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>29.8%</td>
<td>8.8%</td>
</tr>
<tr>
<td>No</td>
<td>33.3%</td>
<td>28.1%</td>
</tr>
<tr>
<td>Total</td>
<td>63.2%</td>
<td>36.8%</td>
</tr>
</tbody>
</table>

3.3.7 Purpose of Use

The majority of respondents use their main analysis tools for more than one purpose. For example the optimisation, design and sizing of the building and its components as well as understanding how that design will function. The primary task of the HVAC respondents is plant sizing and the internal environmental performance. In addition a quarter of respondents use the simulation tool to confirm compliance with design codes.

3.3.8 User Experience

The levels of experience of those taking part in the survey are given in Figure 5. The figure indicates that the majority of respondents rate their own experience level as either ‘adequate’ or ‘competent’ in the use of: 2D graphs, building analysis, web pages, spreadsheets, search engines and 3D graphs. While the majority classed themselves as ‘beginners’ in the use of databases. The experience levels associated with 3D environments show a steady progression from ‘never used’ through ‘beginner’ to ‘adequate’. Finally very few users have experience with voice recognition.
The Application of Visualisation Techniques to the Process of Building Performance Analysis

Figure 5 – Results of the question “Please rate your level of experience for each of the following?”

The questionnaire has provided significant information about the respondents and their use of analytical tools. However, it was not designed to capture details of the tasks users undertake during the simulation.

4.0 Task Analysis

In order to gain further details of the analytical process a Task Analysis (TA) was carried out. The most common method of TA used is interviews (22). This type of interview is generally semi-structured with the interviewees describing the tasks they carry out followed by probing questions on predefined topics. For the purpose of the research presented only Building Services Engineers were considered for the TA process.

4.1 Interview Design & Implementation

The purpose of the interviews was to gain an understanding of the three main stages of analytical design; Model validation, Simulation and Presentation. Semi-structured
interviews rely on a set of prompts to guide the conversation. The prompts used were based on a checklist devised for a user study by Nielsen et al (23). The checklist consisted of eight questions; the first was ‘Why do you do this?’ The next section of the interview was to outline the stages of the analytical process to the subject (24) and then inform them of the three specific stages being investigated. The remaining questions from the checklist were then repeated for each of these stages. The final question referred to the possible existence of eight predefined activities as proposed by Salisbury (25), See Table 7.

Table 7 - Questions used to identify the existence of activities.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Question (yes indicates presence of activity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparison</td>
<td>Are you interested in how the data values relate/compare to each other?</td>
</tr>
<tr>
<td>Optima</td>
<td>Are you looking for maxima or minima within the data?</td>
</tr>
<tr>
<td>Trends</td>
<td>Are you interested in the way your data changes or behaves over a time period?</td>
</tr>
<tr>
<td>Relationships</td>
<td>Are you interested in how some of the data sets relate to each other or affect the values of other data sets?</td>
</tr>
<tr>
<td>Aggregation</td>
<td>Are you interested in classifications within some data sets?</td>
</tr>
<tr>
<td>Distinguishing</td>
<td>Are you interested in individual data values within the data sets?</td>
</tr>
</tbody>
</table>
| Spatial       | Is spatial location important for at least one of the data sets? (Is it important to know the relationship of the variable to objects [600 watts through window 3] or the objects spatial location [window 3 in wall 2]?)
| Calculations  | Do you need to perform numerical calculations (summation, subtraction, multiplication, etc.) on data within or between data sets? |

Six subjects were selected from those building services engineers who had completed all sections of the questionnaire and left contact details (16 in total). These individuals were identified as having different levels of experience but all using the same analytical tool. The interviews were used to build profiles of the users based on the steps they took to validate, analyse and present their simulation results. The following findings are based on a qualitative analysis of the six user profiles.

4.2 Interview Findings

These are presented in the order of the three main simulation tasks.

4.2.1 Model Validation

Model validation comprised the greatest number of unique activities making it the most time consuming stage of the process:

- independent and peer review of input parameters including model geometry;
- read output tables and summary values;
- establish if set points have been achieved;
- identify maximum and minimum values;
- graph key values and perform visual check;
- calculate values per unit floor area or element (e.g. window);
- check values against design specification;
- check values against design guides;
- perform sensitivity study (e.g. change input and check output);
confirm values with hand calculations or independent software;
peer review of output.

These activities involve working with the greatest variety of input and output variables, including; air/surface/supply temperature, heat gains, construction elements, internal/solar/plant loads, absorbed/transmitted solar radiation and weather data. For the variables Air Temperature, Air Changes/Hour and Solar Gains six of the eight tasks listed in Table 7 were performed by all participants. The Six tasks were Comparison, Optima, Relationship, Spatial, Trends and Calculations. The Distinguish task was not directly identified as important by interviewees as they were mainly interested in Trends and Optima. However it is noted that the distinguish task is integral to many of the other tasks (i.e. calculations, comparisons) as it is used to pinpoint single values prior to performing those tasks. The Aggregation task was not identified at all.

When asked about problems and errors encountered during the validation process the interviewees noted that it was easy to become entrenched in the process. Furthermore only after a period away from the model was it possible to spot some types of errors. Some input errors may have little perceivable impact on the simulation results, reducing the effectiveness of sensitivity analysis, but can have a large influence on the conclusions drawn from the data. Input errors are often associated with the user; misunderstanding the required data (units etc.), not knowing the implications of interface settings or simply forgetting to set/reset a value. The interviewees believe that these problems are compounded by the separation of input data across multiple tables/dialog boxes thus making it difficult to review. A similar criticism is made of the output data, especially when considering the results of several simulations. It was also noted that textual descriptions of building components (such as surfaces) were confusing making it difficult to identify which elements data was associated with. The interviewees stated that some improvements were required in their present tools to obtain a clear overview of the input and output data.

4.2.2 Simulation

Once the model is performing as desired the interviewees continued to perform their simulation and analyse the results. In all cases the simulation included a sensitivity analysis, ranging from 2 or 3 runs to a maximum of 25. The comparison of results focused on:

- mathematical Measurement (average & standard deviation);
- peak values;
- target thresholds;
- dynamic behaviour.

The comparisons were made using a mixture of tables and charts. Examples of these indicate that the interviewees preferred to plot multiple variables on separate charts. Another trend was to produce a single datasheet for each analysis run; this allowed multiple runs to be compared side-by-side. Problems identified at this stage included; input errors, model limitations and program errors (bugs).
4.2.3 Presentation

The level of presentation varied. One interviewee rarely presented the results, instead they were used to size components. Others produced reports, either as a brief summary email or as a long technical document and one regularly presented the results in person. Points of interest include:

- ‘I no longer have to avoid colour due to printing restrictions as all reports are issued electronically’;
- ‘The format used to present the results depends on the size of paper used for the report’;
- ‘The idea had already been sold to the client so fancy graphs were not required, just reassurance that it would work’;
- ‘Tables take longer to produce than charts [using the wizard] so I just use charts’.

These comments highlight several important issues. Firstly there are likely to be external influences which dictate the use of certain presentation techniques. Secondly although the data exists the user may not wish to report it in its entirety or spend additional time preparing it in the most appropriate format.

5.0 Conclusion

A significant number of engineers responding to the survey are dissatisfied with the way that their analytical tool presents the results. Although this was not directly identified as a barrier to the use of simulation it is related to issues that were. Because of the lack of training, infrequent use and the desire to increase the efficiency of the analytical process it is recommended that researchers and developers focus on providing tools that explicitly support the users to:

- check the input has been entered correctly (including geometry);
- obtain an overview of the analytical input and output data;
- present both input and output at a peer review;
- identify how output variables relate to each other and the input data;
- understand the influences of changes to the models geometry;
- compare the results of multiple analyses.

The combined findings of the questionnaire and interviews suggest the users commonly need to compare multiple analysis files for validation and design optimisation purposes. Managing and comparing multiple files is not commonly supported by simulation tools. Users often employ post-processors such as spreadsheet packages. These are often customised to support specific tasks. Whilst customising spreadsheet applications has many benefits, see Pilgrim et al (11), it has limitations. In particular 3D geometry is not supported and there are a limited number of inbuilt
visualisation techniques. Research into improved 3D representation techniques is recommended because:

- the respondents reported sufficient experience with 3D graphs and some experience with Virtual Environments;
- fewer respondents were dissatisfied with their presentation tool if it mapped the data to the geometry;
- respondents believed in the potential of VR to enhance the visualisation of their data.

Any technique must be capable of supporting the following activities: Comparison, Optima, Relationship, Spatial, Trends and Calculations and Distinguish. In addition the techniques should aid the user in presenting the data as well as understanding it.

The survey suggests that users are dissatisfied with the current presentation of results whilst others identified problems which may be associated with poor representation. Further work is required to classify the input and output data in a way which will support the selection of appropriate visualisation techniques. Particular focus should be placed on three-dimensional techniques and the integration of data and geometry.

6.0 Acknowledgements

The work detailed within this paper was carried out in partial fulfilment of the EPSRC Engineering Doctorate scheme at The Centre for Innovative Construction Engineering (CICE), Loughborough University. The Research Engineer, Matthew Pilgrim, is sponsored by Arup Research and Development where the work forms part of his responsibilities to provide appropriate tools to the firms’ engineers.

7.0 References


9. IBPSA, Workshops on Next Generation Building Energy Simulation Tools, IBPSA News, Volume 8, Number 1, pp 2, July 1996

10. IBPSA, Workshops on Next Generation Building Energy Simulation Tools – Part 2, IBPSA News, Volume 8, Number 1, Page 1, April 1997


APPENDIX E  PAPER 5 (UNPUBLISHED)

Full Reference:

Novel Representation Techniques for Building Analysis Data

Abstract:

Building performance simulation is a complex process. The simulation engineer is required to enter an accurate model of the space, its occupants and surroundings and interpret the large quantities of data generated by the analytical tool. The work presented here aims to improve the efficiency and accuracy of the interpretation stage. We present a number of novel techniques generated from a four year research effort which included two previous prototypes, a review of existing theory and extensive user requirement gathering. The techniques which have been implemented within a single prototype have been tested by infield engineers and the results are presented. Key developments include the coupling of XML (eXtensible Markup Language) comparison routines to force directed graphs to generate overviews of file content. This and other the techniques described have the potential to change the way engineers interpret their simulation results.

Keywords:

Prototype, Evaluation, Visualisation, Building, Thermal, Performance, Analysis, Data, Interactive, Undirected Graph, Comparison, Tree, 3D, Rule, XML
1.0 Introduction

The overall aim of the research project is to identify and demonstrate visualisation techniques for the improved accuracy and efficiency of thermal analysis data interpretation. Previous work has reviewed current practice [1], developed Web3d [2] and Augment/Virtual reality prototypes [3] and surveyed user requirements [4]. Alongside this, an extensive review of existing theory has been conducted. The work presented here is the final stages of the research where the ideas generated during its course are implemented and evaluated. A solution for each problem area identified was developed within a single prototype and distributed to a number of users for infield testing. A short questionnaire and follow-up interview were used to gather information on the effectiveness of the prototype. The key findings are reported alongside recommendations for future work.

2.0 Context

The research was conducted to fulfil the requirements of both an industrial sponsor and an Engineering Doctorate (EngD) at the Centre of Innovative Construction Engineering, Loughborough University. At the core of the EngD is the solution of one or more significant and challenging engineering problems with an industrial context. Although the solutions presented are believed to be applicable to wider industry they were developed for and tested within a single sponsoring company. Two key attributes of the sponsoring company are: analytical software are developed in-house; these software are distributed to engineers throughout the company (as opposed to select groups of specialists). In-house software development has the advantage of allowing research to be conducted by altering the analytical tools’ source code. However distributed and non-specialist end-users make it difficult to assess the effects of these alterations.

3.0 Development Areas

The thermal analysis of a space within a building requires the user to; enter data about the space and it’s components, set some runtime parameters for the simulation engine, wait for the analysis to complete and begin interpreting and presenting the results. This process is often repeated several times over.

The prototype visualisation system presented in this paper focuses on facilitating interpretation of simulation data through improved representation of multiple models. This is achieved through several functionalities, each implemented on a single tab of a multi-tab dialog (analogous to labels pinned to the top of files in a filing cabinet). A prior investigation of user requirements [4] identified six key tasks which should be supported. These are listed in Table 1.0 alongside the name of the tab designed to support them.
Table 1.0 – Key system tasks and the corresponding dialog tab

<table>
<thead>
<tr>
<th>The system should support the users to…</th>
<th>Dialog Tab</th>
</tr>
</thead>
<tbody>
<tr>
<td>A) Check the input has been entered correctly (including geometry).</td>
<td>File, Overview, 3D View</td>
</tr>
<tr>
<td>B) Obtain an overview of the analytical input and output data.</td>
<td>File, Overview &amp; Result Analysis</td>
</tr>
<tr>
<td>C) Present both input and output at a peer review.</td>
<td>All tabs</td>
</tr>
<tr>
<td>D) Identify how output variables relate to each other and the input data.</td>
<td>Result Analysis &amp; Comparison</td>
</tr>
<tr>
<td>E) Understand the influence of changes to the models geometry.</td>
<td>3D View</td>
</tr>
<tr>
<td>F) Compare the results of multiple analyses.</td>
<td>Result Comparison</td>
</tr>
</tbody>
</table>

The key requirement of each tab, the proposed functionality and the steps taken to develop it are presented in the subsequent sections. A list of tools used to develop the prototype are listed in Table 2.0.

Table 2.0 – Prototype development tools

<table>
<thead>
<tr>
<th>Element</th>
<th>Tool Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main application</td>
<td>Microsoft’s Visual Basic.Net language [5]</td>
</tr>
<tr>
<td>3D interface</td>
<td>Direct3D available in Microsoft’s DirectX 9.0b SDK [6]</td>
</tr>
<tr>
<td>Tables and graphs</td>
<td>VB.Net controls available from ComponentOne [7]</td>
</tr>
<tr>
<td>XML comparison</td>
<td>XML Diff 1.0 differencing engine from Microsoft [8]</td>
</tr>
<tr>
<td>Undirected graphs</td>
<td>WinGraphViz COM object from GraphViz project [9]</td>
</tr>
<tr>
<td>XML editing</td>
<td>XMLSPY and XMLSPY Stylesheet designer [10]</td>
</tr>
</tbody>
</table>

Key to the prototypes development was the combination of Visual Basic .Net (VB.NET) and XML. VB.NET, a visual programming language, when used in conjunction with Microsoft Developer Studio facilitates rapid development of powerful data driven applications. The XML standard made it possible to quickly define new data structures and then by applying transformations (a part of the Extensible Style Language, XSL) alter both the structure and appearance of the data. See Sawhney [13] for a brief overview of XML and its use in the construction industry.

3.1 File Organisation & Data Checking (File Tab)

Conducting a single analysis using the sponsors simulation tool (ROOM) results in the generation of three files, containing; Input, Runtime and Output data. The user will typically carryout a number of ROOM analyses by altering the input and/or runtime files and running the simulation using different combinations. Interviews of the sponsors’ engineers [4] identified validation of simulation data was complicated by the number of disparate files involved in the analytical process, i.e. tracing which input/runtime data was used for each analysis. The following proposals address this.
Proposal: Integrate all data in one file; import all files into one project.

Proposal: Present a raw or formatted view of each complete dataset.

The first step in developing the prototype was to write all three sets of data to a single XML file after each analysis. These files are then referenced from a project file created by the engineer using the prototype. The project file stores details of each XML file; path, title (used to identify the file) and description. Whilst file management of this type is not new it is central to the prototype’s ability to offer an intuitive user interface. The entire set of analysis data is available to the user in raw XML format or transformed into tables to improve readability. This is the first time that the user has been presented with all the analysis data in a single consistent form (which is also machine readable), See Figure 1.

Key to the successful application of XML files was the selection of tag names. There are practical considerations; firstly the tags must be descriptive enough to allow the human reader to interpret their meaning, secondly only objects of the same type should have identical tags. Following these two rules it was possible to produce an XML file which was both readable and could be used to automatically produce an accurate schema. The schema, with the aid of a stylesheet designer, was used to produce a number of stylesheets to transform the structure and presentation of the data files.
3.2 Differences between Models (Overview Tab)

Engineers regularly analyse a number of design options to understand the sensitivity of both the design and the numerical model used to analyse it. Each design option now results in a single analysis file compatible with the prototype system. As the number of design options and therefore files grow it becomes increasingly difficult to keep track of which parameters remain constant and which have been changed. The following proposals capitalise on the structure of the XML files used to store the data.

Proposal: Compare files and graphically display similarities and differences.

Proposal: Enhance display to include an indication of the models performance.

XML files consist of a hierarchy of nodes, each node may have a number of attributes and contain either a value or a child node. This structure allows nodes and their data to be easily accessed and modified. Here, we use XPaths (a query language) to retrieve nodes and form sections of data. These sections can be constructed from any number nodes grouped by any number of criteria from any number of separate files. By comparing these sections, using an XML differencing engine\(^9\), it is possible to construct a network of objects that describe which sections of data are the same and which are different. The following steps are used to identify identical (therefore unique) sections of data (note this excludes output data) in multiple files:

1. Decide on which nodes belong to which section.
2. Group files’ nodes under the appropriate section.
3. Compare each section of each file with the same section of every other file.
4. For each comparison made: If the sections match then check each Unique Section Object already created to see if the file that the section belongs to is already referenced. If either section is referenced then add a reference to the other, if both are then do nothing, if neither is then create a new Unique Section Object and add references to both.
5. After all files are checked some sections will remain unreferenced by Unique Section Objects, these files share no common section data and therefore have a Unique Section Object created and referenced to the file.

The resulting Unique Section Objects represent data found in one or more files and contain references to these files. Further objects are used to maintain references from files to Unique Section Objects and store the appropriate data. This information is displayed for the engineer using diagrams, known from here on as Force Directed Difference Diagrams. Firstly nodes are created for each file and each Unique Section Object. Secondly links are created between the nodes according to the references stored on the Unique Section Objects. The resulting undirected graph [14] is processed using the WinGraphVis layout component (See Table 2.0) which produces a force directed diagram rendered using Scalable Vector Graphics (See Table 2.0), See Figure 2.

\(^9\) Ms XML Diff & Patch was used but alternatives are available from versim.com and deltaxml.com.
Figure 2 – Comparing Input and Runtime Sections

Figure 2 illustrates three files (Blue hexagons) being compared using sections which represent the Input (Pink Rectangle) and Runtime (Purple Rectangle) data. Note that when categorised and arranged in this way the files share no common sections of data, i.e. the user changed different data in each section of the file. However if the way in which the data is categorise into sections is changed then a different diagram emerges, Figure 3.
Figure 3 – Comparing Architecture, HVAC and Occupancy sections

In this case the data are split into three sections, representing Occupancy, Architecture, HVAC. Now it is evident that the user fixed the occupancy in Files 1 and 2 but altered HVAC and Architecture. Also the Architecture in Files 2 and 3 is the same but the Occupancy and HVAC differs.

This powerful technique allows the user to rapidly understand the similarities and differences between multiple files using a number of classifications. Further support is offered by displaying the data contained in each section (by clicking on it) and by displaying the differences between two sections (by picking each in turn).

The diagram, in this form, displays the differences between the data used to drive the analysis but not the results produced by it. If the user wishes to quantify the impact of varying the input data then the option is given to map one or two output parameters to the file icons position, see Figure 4.
The Application of Visualisation Techniques to the Process of Building Performance Analysis

Figure 4 – Quantifying result data

Here the blue file icons are positioned left to right with increasing internal air temperature and bottom to top with increasing internal humidity. The links indicate, as before, which sections of data belong to which files. The engineer may now discover patterns relating input (same occupancy) data to output characteristics (i.e. cold and humid).

3.3 Single File Numerical Presentation (Result Analysis Tab)

The survey results indicated that engineers are interested in a wide range of data within each analysis file. To cope with the quantity of data within the files the engineers tend to take values for one time step or aggregate time steps over larger time periods. Analytical tools do not support these tasks making it necessary for the data to be imported into spreadsheet packages. Spreadsheets whilst suitable for a wide variety of tasks do not, by default, support actions specific to thermal analysis e.g. locating the hottest day of the month, see [1] for further discussion. The following proposals support the majority of tasks specific to analysing the results of a single analysis.

Proposal: Calculate common aggregates for each variable

Proposal: Display a monthly summary of aggregates

Proposal: Link aggregated variables to daily values

Proposal: Allow variables to be sorted according to biggest/smallest values
Proposal: Automatically plot selected variables

Figure 5 shows the interface designed to support these processes. On selecting an analysis file the user is presented with a list of items to display. These items are constructed from each variable within the file plus a number of measures (aggregates). Examples of the aggregates include: Minimum, Maximum, Average, Summation. The items display the name, details of which aggregates are appropriate and an XPATH to the data are stored in a separate XML file (allowing customisation). Note: at this point the user may opt to switch between different sections of data, relating to the whole month, just one day or the spaces’ surfaces. On selecting an item from the list the daily/surface data is displayed in the top most ‘overview grid’ (in the example given: average external temperature, internal humidity and internal temperature). Hourly values for the selected surface/day (in this case day 14) are displayed in the lower ‘details grid’ for each variable. The choice of which day/surface to display details for is aided by allowing the user to sort the rows of the master grid by clicking on column headings (brings either largest or smallest value to the top). The detail grid also highlights the minimum and maximum values.

![Image of interface](image)

**Figure 5 – Single file analysis, columns selected**

Data from either grid is easily plotted by selecting the appropriate row(s), column(s) or cell(s). Columns and cell ranges are plotted as line charts (two highlighted columns plotted in figure) with one or more series representing each variable. Rows of data are plotted as bar charts for the given hour or surface (See Figure 6).
3.4 Multiple File Numerical Presentation (Result Comparison Tab)

As well as inspecting the contents of individual files engineers often plot variables from multiple files together. They also plot different variables from the same file on the same chart. The process of gathering the correct data from each file and presenting it can be time consuming. In addition charts are generally restricted to output data, omitting vital information. The following proposals support the majority of tasks specific to analysing the results of multiple analysis files.

Proposal: List only the compatible input and output variables for the selected files.

Proposal: Allow selection of individual objects/time periods.

Proposal: Automatically produce tables and graphs for selected items.

A key feature for the presentation of the multiple file/variable data is the tree view component. On selecting the first analysis file its key variables are mapped to nodes on the tree using an XML control file. This clearly displays the hierarchy and origin of each variable. By combining each leaf node with a checkbox the user can control which data is selected. If the file does not contain data for a particular leaf node then the check box is greyed out (unavailable), see Figure 7.
As additional files are selected the tree is pruned further to remove incompatible variables. There are three types of checks used on each variable node when a file is added:

1. The node is present in the added file.
2. The same number of child nodes is present in both the parent and added file.
3. The id and names of each child node match in both the parent and added file.

Each variable has a preset check level (stored in the XML control file) and if the variables in the added file fail the check then the relevant variable is greyed out in the tree. This ensures that as files are added only variables where the data is compatible are displayed. As the user selects variables in the tree a further set of checks is performed and the tree is pruned again. These checks ensure plotting compatibility and are based on the following four types of variable (example in brackets):

1. Object (Area per Surface)
2. Object + Time (Temperature per Surface v Time)
3. No Object (Room Volume)
4. No Object + Time (Heating Temperature v Time)
Variables are compatible as long as they are the same type, and in the case of Type 1 the objects are the same (i.e. fulfil Check 3). This ensures that the checkboxes which remain available for user selection will produce a sensible selection of variables for plotting. Note: when variables of Type 1 or 2 are selected the associated objects are displayed in a variable control area ready for the user to specify which ones to plot. In addition if variable Types 2 or 4 are selected then the appropriate time period is displayed ready for user refinement. When the user has finished selecting the options presented to them the data grid is populated and a chart plotted. The plot type and grid layout depend on the number of files and the type of variables selected (details omitted for brevity). Thus the complicated process of comparing multiple files and variables is reduced to 3 easy steps using some relatively simple rules.

3.5 Geometry Presentation (3D View Tab)

A significant proportion of thermal analysis data is related in some way to the spaces geometry. Whilst tools are generally provided for the modelling of this geometry few exist for the interpretation of data related to it (surface area, boundary conditions, temperature etc.). The following proposals address key user requirements.

Proposal: Interactively display selected models geometry.

Proposal: Link models surfaces to relevant data.

Proposal: Remove unwanted surfaces.

Proposal: Colour code the remaining surfaces using input and output data.

Whilst work is ongoing to explore ways to graphically display complex data on individual (and generally irregular) surfaces, the number of possible solutions appears limited. The approach taken here is to allow the user to map a single variable to the colour/visibility of each type of surface (presently limited to Standard surfaces and Windows). The visibility is used to hide surfaces which are not of interest or obscure data that is. Surface visibility is controlled as follows:

1. Manual – A tree component represents each surface of each file as a node with a checkbox. Files are displayed by selecting the check box and surfaces hidden by clearing the checkbox.
2. Automatic – All surfaces which face the user are automatically removed leaving only the rear surface (allowing the viewer to see the inside of the space).
3. Rules – Further surfaces may be hidden by applying rules. Rules are based on variables associated with each surface type and can be easily combined, see left of Figure 8.

Surface colour is also controlled by applying rules to each type of surface, see right of Figure 8.
Both rule builders permit numerical variables to be aggregated over a given time period. This allows the user to map multiple hours to a single surface. Once again the functions available for each variable are controlled by a separate XML file. Figure 9 shows the results of several rules being applied simultaneously. In this case the rules are:

1. Hide all surfaces where the value of Temperature > 30.0 °C
2. Colour code surfaces by maximum temperature found between 9:00-17:00.
3. Colour code windows according to the number of element layers used in their construction.
The perception of different surface properties is aided by colour coding. Colour Perception is dealt with by Hartridge [15] and Friedhoff [16] while Bergman [17] describes practical colour selection and application. Here colour coding of the surfaces was carried out either to associate the surface with a category or a range of continuous values. Categories were encoded with colours as different as possible, continuous values were encoded using a heated object scale. The heated object scale is both intuitive to the domain users and has more distinguishable display values and more contrast between different levels than a grey scale [18].

The key to successful three dimensional displays is the navigation method used. Having used a number of techniques in previous projects [2, 3] it was clear that a single method was required that made it easy to inspect both the interior and exterior of a model. We therefore choose to fix a rotation point in the centre of the model thus allowing simple movement of the space. The drawback of this decision is that a single model must be selected for it to work. When the user wishes to display multiple models they are arrayed in a circle which rotates the selected model (indicated by a red grid) to the front of the screen, see Figure 10.

![Figure 10 – 3D geometry, multiple models](image)

This allows the user to compare multiple models (in the background) whilst easily explore the selected model. Model, surface and window selection is supported by double clicking the 3D view or selecting the item in the tree component.

4.0 Prototype Evaluation

The evaluation of the prototype was driven by the following question:
“Do the proposed techniques have the potential to improve the accuracy and efficiency of analytical data interpretation within the sponsoring company?”

A significant difficulty in evaluating specialised applications such as the prototype is that it is a domain expert tool. In contrast to evaluating a more common software, such as a web browser, the number of practising domain experts within the sponsoring company is very small [19]. In order to overcome this problem it was decided to undertake a two-part evaluation. The usability of the prototype was assessed using a combination of heuristic evaluation and user testing as advocated by Nielsen [20].

4.1 Heuristic Evaluation

The heuristic evaluation was a partly formative and partly summative process carried out by the developer where the following guidelines were used to both lead and revise the design:

- Shneiderman [22] on the properties of Information Visualisation systems.
- Salisbury [23] on which user tasks to support.

Examples of heuristic guidelines and their application are included in Figure 11.

<table>
<thead>
<tr>
<th>Two Heuristics from the Top Ten list (Nielsen, 1994)</th>
</tr>
</thead>
</table>
| 1) **Recognition rather than recall** - Make objects, actions, and options visible. The user should not have to remember information from one part of the dialogue to another. Instructions for use of the system should be visible or easily retrievable whenever appropriate.  
*There are no hidden menu options, all controls are visible. If they are inappropriate to the current operation then they are greyed-out.*  
2) **Help and documentation** - Even though it is better if the system can be used without documentation, it may be necessary to provide help and documentation. Any such information should be easy to search, focused on the user's task, list concrete steps to be carried out, and not be too large.  
*Each tab of the dialog has a web browser, this when not occupied by the users data contains help specific to that tab.* |

<table>
<thead>
<tr>
<th>Two Heuristics from the Visibility of System Status section (Xerox, 2003)</th>
</tr>
</thead>
</table>
| 1) **Is there some form of system feedback for every operator action?**  
*Every action within the interface takes immediate effect. If the process is slow then a progress bar indicates the action has started and when it is due to complete.*  
2) **After the user completes an action (or group of actions), does the feedback indicate that the next group of actions can be started?**  
*The controls are laid out in a sequential fashion indicating to the user that they should move from the top left to the bottom right in order to initiate a process. Each group of controls is only enabled when they are applicable, further leading the user through the process.* |

Figure 11 – Examples Heuristics
The use of heuristics helped to ensure that obvious usability issues were removed before engineers were exposed to the interface. Table 3.0 summarises the functions associated with each of the properties identified by Shneiderman [22]. Note: the filter and extract categorises have been merged because there was little difference between the functions. In addition the history task is not supported; this is because each function is easily reversed.

Table 3.0 – Task support by tabs of the Prototype

<table>
<thead>
<tr>
<th>Task</th>
<th>Files</th>
<th>Overview</th>
<th>Result Analysis</th>
<th>Result Comparison</th>
<th>3D View</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overview</td>
<td>All files listed. TOC displayed at top of file. Tree view shows document structure.</td>
<td>Diagram is an overview. All files clearly listed.</td>
<td>Master table shows overview.</td>
<td>All files listed and variables displayed in a tree view.</td>
<td>All models listed or displayed in 3D.</td>
</tr>
<tr>
<td>Zoom</td>
<td>One file can be selected. TOC can be clicked. Tree nodes can be expanded.</td>
<td>Diagram can be zoomed and panned.</td>
<td>Selecting a row generates a detail table.</td>
<td>Adding a variable removes incompatible variables.</td>
<td>View can be rotated, zoomed and panned.</td>
</tr>
<tr>
<td>Filter/Extract</td>
<td>None.</td>
<td>Selection of different: - files - diagram type - variables.</td>
<td>Display only selected variables. Plotting selected row/columns.</td>
<td>Display only selected objects and time period</td>
<td></td>
</tr>
<tr>
<td>Details-on-demand</td>
<td>As in Zoom.</td>
<td>Click files or icons for details.</td>
<td>Selecting a row/column shows details.</td>
<td>Selecting a file gives details. All data plotted in several clicks.</td>
<td>Click model/surface for details. Surfaces colour coded.</td>
</tr>
</tbody>
</table>

Heuristic evaluation is a recognised alternative to costly and resource intensive usability engineering\(^\text{10}\) (Preece, 1994). In the present case it was complemented by infield tests as recommended by Jeffries et al. 1991 and Karat et al. 1992.

\(^{10}\) Defined by Tyldesley (1988) as ‘a process whereby the usability of a product is specified quantitatively, an in advance. Then as the product is built it can be demonstrated that it does or does not reach the required levels of usability’.
4.2 Infield Testing

In order to best capture the potential of the proposed techniques the prototype was designed to be used by engineers in their standard working environment. This is in contrast with the test environment (training room) used to evaluate the very first research prototype. Whilst this offered the advantage of carefully controlling the type of equipment used and the tasks undertaken the prototype was used in an artificial manner. This was appropriate for measuring the performance of certain aspects of the design but less appropriate for investigating the real world potential. A number of engineers who currently use the ROOM analysis package were therefore asked to install the prototype and apply it to existing/new analytical data. Following its installation each user was either shown or talked through each aspect of the prototype. They were then left unsupervised for a one month period. During this time the prototype generated a log of usage which included details of which tabs were used and for how long. At the end of the test period log files were collected and the engineers given a short feedback questionnaire. The questionnaire consisted of 11 key questions designed to determine if the prototype had fulfilled the main research aim (as stated in Section 1.0) and the six key requirements (as stated in Table 1.0). The results of the questionnaire were analysed and used to aid discussion in a follow-up telephone interview. Analysis of the log files, questionnaires and interviews follow.

4.3 Evaluation Results

The aim of the research was to demonstrate and evaluate visualisation techniques identified as suitable for improving the interpretation of building performance data.

The demonstration aspect of the research has been partially fulfilled through the infield evaluation presented here. In conducting the evaluation, details of the prototype system were sent to all engineers within the sponsoring organisation who currently use the ROOM analysis package (approximately 40 in number). This prompted requests to participate from 23 users around the world, of which 9 eventually completed the evaluation. All 9 participants were UK based; the remaining 14 who did not participate were predominately based in America or Australia. When asked why they had not started the trial these users generally responded that they did not have time to install the prototype. The following results are based on the analysis of 9 log files, questionnaires and follow-up interviews.

Summary of use

Four engineers used the prototype once when it was first installed, four more used it several times to test its functionality and one used it every time the ROOM program was used. On average the prototype was initialised six times per user for fifteen minutes per session. Five of the users explored the entire interface, two experienced code errors stopping them from using all the tabs and two further users had insufficient time to use all the tabs. Figure 12 shows the average time that the users spent on each visit to individual dialog Tabs and the corresponding number of visits. However it should be noted that on initialisation the prototype defaults to the File tab, therefore the number of visits and time recorded are likely to be distorted.
Figure 12 – Use of dialog tabs stated in time per visit and number of visits

Ignoring the Files tab, the figure illustrates that the Overview tab had the largest number of visits (53) with users spending on average 2.2 minutes per visit. Whereas the 3D View has the second largest number of visits (47) with users spending over double the amount of time per visit (5.3 minutes).

For the purpose of the evaluation eight of the nine users inspected data from previous projects and five of the nine users inspected data from their current project. Seven of the nine users also showed the prototype to one or more engineers.

Accuracy and Efficiency

The main aim of the prototype was to improve interpretation of the analytical data. Improvement is measured by the reduction of errors and a decrease in the time taken to arrive at the correct results. As the prototype was evaluated by the engineers within their workplace these variables are difficult to quantify. Instead indirect qualitative measures based on user feedback were used. When asked to rate the prototype as a tool for visualising building performance data five users rated it as slightly good and four as very good. When asked if the prototype improved the accuracy and efficiency of their data interpretation two users neither agreed nor disagreed, four users slightly agreed and 3 users strongly agreed. This is supported by four users stating that they discovered new information from their data and three users found previously undetected errors within their data. The 3 errors were:

1. Reversed ventilation areas – The user compared multiple files with the Force Directed Difference Diagram (Overview tab) and found differences between the Runtime section of files which should have been the same. The error was confirmed by comparing the vent areas using the Result Comparison tab.
2. **Missing surface** – The model when displayed in the 3D view had a surface missing which was not detected using the existing wire-frame view in the input program.

3. **Incorrect boundary condition** – Each surface of an eighty surface model was colour coded according to its predicted temperature. The user quickly identified an unusually cold surface which was discovered to have an incorrect boundary condition.

Statements obtained from the interviews also suggest improvements in accuracy and efficiency, these include:

1. “The comparison is much quicker than scrolling down to the one key cell in several csv files [present output format], and easily lets you see the significant difference”

2. “I liked the summary of the whole model on the File tab as it saves looking at different dialogs”

3. “The presentation made it easier to understand and navigate/locate data”

In order to evaluate the prototype against the six task requirements stated in Table 1.0 the users were asked to state which tool (and which function) they would use to complete each of the tasks. They were given the choice between all of their existing tools and the prototype, see Table 4.0 for the encoded responses.

**Table 4.0 – Chosen tool for each task: E=Editor, R=ROOM, S=Spreadsheet\(^\text{11}\) and P=Prototype (where tabs are identified by: F=File, O=Overview, A=result Analysis, C=result Comparison & 3=3D View). Note: dark grey represents the prototype only and light grey represents the prototype plus another tool.**

<table>
<thead>
<tr>
<th>Task Requirements</th>
<th>User Initials</th>
</tr>
</thead>
<tbody>
<tr>
<td>A) Check the input has been entered correctly.</td>
<td>RS KH MC JY CR DM CM KK DC</td>
</tr>
<tr>
<td>B) Obtain an overview of the analytical data.</td>
<td>RS KH MC JY CR DM CM KK DC</td>
</tr>
<tr>
<td>C) Present the analytical data in a peer review.</td>
<td>RS KH MC JY CR DM CM KK DC</td>
</tr>
<tr>
<td>D) Understand the influence on the results to changes in geometry.</td>
<td>RS KH MC JY CR DM CM KK DC</td>
</tr>
<tr>
<td>E) Compare results of multiple analysis.</td>
<td>RS KH MC JY CR DM CM KK DC</td>
</tr>
</tbody>
</table>

\(^\text{11}\) The spreadsheet included macros for formatting and plotting multiple files as described in [1]
A clear majority of users voted to use the prototype instead of existing tools for three of the five tasks:

4. Task B - The users seemed to disagree on the most appropriate Tab of the dialog, indicating that there are many ways to gain an overview of the data.
5. Task D - Five out of the nine users said they would use the Comparison tab and four out of nine said the 3D View tab. This illustrates that users are equally happy to inspect the results in tables and in 3D even if the results are affected by changes made to the models geometry.
6. Task E - Seven of the nine users would use the Comparison tab of the prototype, with two users combining this with a spreadsheet. The interviews indicated that the speed of comparison was highly important followed by the need to customise the final graphs, hence the use of a spreadsheet package.

Of the remaining two tasks (A & C), the first involved checking the input data which the majority of users would carry out using the input editor, and the second was data presentation at a peer review meeting. The prototype, as tested, did not have the ability to save or print the tables, graphs and images required for a peer review thus accounting for the high number of users who would use a spreadsheet for this task.

Specific features

Table 5.0 shows that all tabs of the prototypes dialog, except the file tab, were rated as either slightly or very useful.

Table 5.0 – Most common rating assigned to each tab

<table>
<thead>
<tr>
<th>Name</th>
<th>Files</th>
<th>Overview</th>
<th>Analysis</th>
<th>Comparison</th>
<th>3D View</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rating (no. times / 9)</td>
<td>Neutral (4/9)</td>
<td>Slightly Useful (5/9)</td>
<td>Slightly Useful (4/9)</td>
<td>Very Useful (5/9)</td>
<td>Very Useful (7/9)</td>
</tr>
</tbody>
</table>

The table indicates that the 3D view was rated as very useful by seven of the nine users and the data presented in Figure 9.0 indicates it was also used the most. However inspection of the text based questionnaire responses and interview logs indicates that the 3D view would not be used for interpreting the analytical data as such. Instead it is more likely to be used to gain an overview of the 3D geometry and create presentation graphics. It is possible that as users have become familiar with the tables and graphs they presently use, it will take some time before they start problem solving using 3D views of their data. It is also possible that the omission of shading devices and the shadows they cast reduced the problem solving ability of the 3D view. Note: the neutral rating of the Files tab reflects its almost entirely administrative role in the prototype.

Of significant interest to the research is the development of new tools and techniques which are intuitive to use. Diagrams, such as the Force Directed Difference Diagram implemented on the Overview tab, are dissimilar from those used on a day to day basis by the engineers. The users were therefore asked if they understood the diagrams and whether or not they used the associated help page. The general consensus was that the diagrams took longer to understand than other aspects of the interface but extra effort was worthwhile. The introduction to each aspect of the interface, given on its installation, was sufficient for most users to understand the diagrams with only a few
referring to the help page. Some users had also clearly thought about the identification of unique sections of data and were keen to discuss extensions to the diagram.

**Problems Identified**

A number of potential problems were also identified during the course of the evaluation. At the start of the trial the software failed to install properly on two machines, this highlights just one of the difficulties in distributing test software. During the course of the trial several users reported problems with the 3D view. These were associated with multiple windows of the same name being incorrectly positioned on a surface; a procedure to avoid the problem was developed. At the end of the trial further problems were identified with the 3D view. Although the navigation of multiple models was apparently problem-free it did raise two separate concerns. Firstly one user reported:

“The 3D view does not seem to show building orientation visually, which is often an important factor when analysing the effects of solar gain. Displaying different models in a circle could actually mislead the user about building orientation”

A second user found it difficult to carryout side-by-side comparisons of surfaces on two or more models (due to their position on the circle). Arraying models around the perimeter of a circle has therefore introduced two problems. These problems may be rectified rotating the model so as to maintain a consistent orientation. In this way all models would face the same way allowing a clear view of the desired surface.

A large number of users also requested additional functionalities, currently not present within the prototype. These were mainly associated with more advanced features in the 3D View and the ability to print or export data and graphics.

**Potential for commercial application**

The willingness of users to imagine further enhancements to the prototype suggests its acceptance as an addition to their present toolset. This is exemplified by the following user statement:

“The software is what ROOM has needed for the past few years; this allows the output from ROOM to compete on a level playing field with it’s competitors and will prove invaluable to presenting data to clients – a really useful package!”

When asked if they would be willing to uninstall the prototype six of the nine said they would be unhappy for it to be removed, the remaining three were unsure.

**5.0 Future Work**

Before the techniques demonstrated by the prototype are implemented in a commercial product it will first be necessary to increase their speed and reliability. This is closely followed by the necessity to implement both printing and exporting capabilities. It is clear from the evaluation that the engineers wish to export tables, charts, diagrams and animations for use within reports and presentations. Further research and development is also required in the following areas.
5.1 Force Directed Difference Diagram

The key to reading Force Directed Difference Diagrams lies in determining which data makes each section of the model unique from other models. The diagrams may be improved by automatically calculating these differences and displaying a summary of them within the diagram. At present if the user selects two unique sections of data (of the same type) then a colour coded text document highlights the differences. This could be further improved, possibly by using co-ordinated colour coded tree views. Finally, the data included in each unique section is predefined by a number of XPATH queries. Within the prototype these sections were limited to Input/Runtime/Output and Architecture/Occupation/HVAC. However it is possible that, with careful design, an interface could be developed to support the user in constructing their own classification of the data. Without research it is not clear whether this is either useful or practical.

Three-dimensional representation

Shading devices and the shadows they cast were omitted from the prototypes 3D View due to complexity of the code required to calculate them. This omission seriously restricts the users’ ability to infer relationships between the suns position, the shading devices effectiveness and the resulting internal conditions. With significant effort this could be included within a commercial version of the prototype. However careful thought must be given to the appropriateness of re-calculating patches of light and shade. These patches are generally calculated by the simulation package and have a significant impact on the spaces predicted performance. Due to their complexity it is possible that the techniques used to render patches of light and shade within the visualisation application will differ from those used within the simulation package. It may therefore be more appropriate to include details of their shape and location in the results section of the XML file. Again this requires further research.

The 3D view suffers from two further, but less critical, limitations. Firstly the appearance of colour coded surfaces is directly related to the position and direction of the light sources. In the case of the prototype a single headlight attached to the viewpoint is used to illuminate the scene. Thus two surfaces of different orientations but with the same value will appear different colours to the user. The advantage of this technique is that it allows the edges of adjoining surfaces to be perceived; the disadvantage is that it reduces the accuracy by which values can be interpreted. Therefore research is required into more appropriate illumination models.

The second limitation is related to the algorithm used to layout multiple models within the scene. At present it generates a circular array of models which is rotated to bring the selected model into view. Whilst suitable for gaining an overview it does restrict the comparison of models. This is because the same façade of two ore more models is not visible from a single position within the scene. Further layout algorithms or multiple side-by-side views are therefore required.

6.0 Conclusion

Previous stages of the research identified key user requirements. This paper documents the functions designed to meet theses requirements and presents an overview of one particular implementation of them. The implementation, in the form of a single
prototype, was tested by engineers and the results of its evaluation presented. The results indicate that, even in a short period of time and with almost no training, the users were able to gainfully apply the prototype. In a number of cases previously undiscovered information and errors were detected in existing datasets. In addition nearly all feedback was positive with no features being identified as unnecessary or overcomplicated. In conclusion the proposed visualisation techniques improved the interpretation of building performance data and have clear potential within the sponsoring company.

7.0 References


15. Hartridge, H. (1949) Colours and how we see them, G. Bell and Sons, London

APPENDIX F SUPPORT MATERIAL

Contents:

1.0 Data Model
2.0 ROOM data classification.
3.0 User profiles.
4.0 Final Prototype Evaluation: Questionnaire
1.0 Data Model

The data model, as presented in Section 4.2.1, is described below. Note: references are included in the main body of this document, see Section 6.

**Domain**

Data is said to belong to one or more domains each of which have heuristics associated with them. For example temperature has particular colour scales associated with it. This list is not exhaustive and could be expanded if data from a particular domain has visualisation techniques associated (Based on Roth 1990, Earnshaw 1992 & Arens 1993).
Origin

As well as belonging to a domain data can be classified by its origin. Here we use the terms Simulated, Measured and Derived. As sensing devices are limited in both quantity and functionality measurement data generally consists of a finite number of samples each with a degree of error. If data isn’t measured then it is typically the product of a calculation (i.e. based on a theory or algorithm of some sort) we refer to it as simulated. The final category is derived data, this represents data which has been processed from its original form; this may include sampling, combining, separating or manipulating raw data sets (Based on Yu & Behrens 1995 & Haber & McNabb 1979).

Atomic

Atomic objects have both a physical state and a conceptual measurement scale. Physical type reflects the way the value is stored and used electronically (Earnshaw 1992). The measurement scale has been the subject of much discussion, with several contradicting views. The traditional model is nominal, ordinal, interval and ratio (referenced by authors as: Data type format – Yu & Behrens 1995, Set ordering – Roth 1990, Order – Arens 1993, Data type – Card 1999 & Scale – Rheingan 2002). These scales are based on seminal work by Stevens (1946) who identified the categories based on the transformations that can occur to a value without the loss of meaning. At one end of the scale Nominal data will tolerate all transformations that preserve the relationship between elements and their identifiers. At the other end of the scale Ratio data will only tolerate multiplication by a constant. Stevens identified which statistical methods are valid for each step of the scale. Velleman and Wilkinson (1993) argue that this classification scheme is not suitable for modern data analysis. They state that Stevens list is not exhaustive and give an example of a ‘counted fraction’, that is a number bounded by 0 and 1. They state that this will not tolerate even arbitrary scale shifts and therefore does not fit Stevens classification. Mosteller and Tukeys’ (1997) scale is presented as a thought provoking alternative. This scale is more intuitive and offers a greater number of categories to associate visualisation techniques with. As such the scale has been adopted here and extended to include binary, cyclic, proportions and percentages categories\(^{12}\). As summary of which is stated below.

Discrete

**Categorical**
- **Binary** - categorical variables with just two states e.g. 1/0 or alive/dead.
- **Names** - More than two categories with no numerical relevance, e.g. soil type.
- **Grades** - ordered labels such as Freshman, Sophomore, Junior, Senior.
- **Cyclic-grades** - ordered labels which loop, e.g. day of week or phase of moon.
- **Ranks** - sequence starting from 1, which may represent the largest or smallest.

**Counted**
- **Counts** - non-negative integers representing the frequency of occurrence.
- **Counted-fractions** - bounded by 0 and 1, e.g. cloud cover in 1/8\(^{ths}\).

\(^{12}\) Durham Geography CAL Website, Statistics: Data Types
URL: http://geography.dur.ac.uk/teaching/level1/module4/4_4/docs/4_4.html
Continuous

- **Proportions** - must add up to 1, akin to counted fractions.
- **Percentages** - must add up to 100.
- **Amounts** – non negative real numbers, e.g. height and weight.
- **Balances** - unbounded, positive or negative values, e.g. temperature (maybe interval or ratio depending on the existence of an arbitrary zero point).
- **Cyclic-balances** - looping values such as 0-60 seconds or -180 to 180 latitude.

Composite

Composite objects are collections of other objects. We therefore need to describe the nature of the collection. If the objects are numerical then we can describe the data by their **distribution** (Yu & Behrens 1995) and by the number of **components** used to make up the quantity. For example a vector has both direction and magnitude and requires a number of scalars equal to the dimensions of the co-ordinate system (Senay 1994 & 1999). The **physical** data type describes the manner in which the collection is stored. **Aggregation** describes the nature of the collection (Earnshaw 1992); a **series** has intrinsic order, a **group/set** is used to collect similar items, a **graph** describes data which has information associated with it’s inter relationships and **mesh** data is related to how the values map to some physical domain for each element (Earnshaw 1992).
# 2.0 ROOM data classification

Numerical data assigned a classification according to its Measurement Scale. Note: if not numerical then Text.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Example</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Title/Subtitle/heading</td>
<td>One line of information</td>
<td>“Façade Analysis for Peter”</td>
<td>Text</td>
</tr>
<tr>
<td>Date</td>
<td>Date the analysis was created or edited.</td>
<td>13-Feb-2002</td>
<td>Grade or Cyclic grade</td>
</tr>
<tr>
<td>Description</td>
<td>Multiple lines of information</td>
<td>“This analysis examines the effects on a, b &amp; c when adjusting x, y &amp; z ..…”</td>
<td>Text</td>
</tr>
<tr>
<td>Person</td>
<td>Name of person (or staff id/Initials) that carried out the analysis.</td>
<td>Peter Smith</td>
<td>Text</td>
</tr>
<tr>
<td>Analysis Type</td>
<td>Describes the type of analysis model used.</td>
<td>Standard or Facade</td>
<td>Name</td>
</tr>
<tr>
<td>Room Identifier</td>
<td>Identifies the specific room analysed – alphanumeric.</td>
<td>Room001</td>
<td>Text</td>
</tr>
<tr>
<td>Volume</td>
<td>Volume of the room.</td>
<td>300 (m³)</td>
<td>Amount</td>
</tr>
<tr>
<td>Month</td>
<td>Month of year used for analysis.</td>
<td>July</td>
<td>Cyclic-grade</td>
</tr>
<tr>
<td>Units</td>
<td>Type of units used for IO.</td>
<td>SI, English or American</td>
<td>Name</td>
</tr>
<tr>
<td>Flow Pattern</td>
<td>Describes the type of flow model used.</td>
<td>Stratified or Fully Mixed</td>
<td>Name</td>
</tr>
<tr>
<td>Latitude</td>
<td>Latitude of site, longitude not important here.</td>
<td>51.5</td>
<td>Cyclic-balance</td>
</tr>
<tr>
<td>Altitude</td>
<td>Altitude of site above see level</td>
<td>10 (m)</td>
<td>Amount</td>
</tr>
<tr>
<td>Orientation</td>
<td>Orientation of site from North and the building with respect to the site.</td>
<td>15 Degrees</td>
<td>Cyclic-balance</td>
</tr>
<tr>
<td>Origin</td>
<td>X, Y &amp; Z values for the building or rooms origin with respect to the site.</td>
<td>0,0,0</td>
<td>3x Balance</td>
</tr>
<tr>
<td>Climatic Data Type</td>
<td>Describes the type of climatic data used.</td>
<td>Cyclic or Sequential</td>
<td>Name</td>
</tr>
<tr>
<td>File</td>
<td>File name and location.</td>
<td>C:\temp\weather.file</td>
<td>Text</td>
</tr>
<tr>
<td>Ground Reflectance</td>
<td>The amount of solar reflected by the ground (0-1).</td>
<td>0.2</td>
<td>Proportion</td>
</tr>
<tr>
<td>Ground Temperature</td>
<td>Subterranean Ground Temperature.</td>
<td>12 (°C)</td>
<td>Balance</td>
</tr>
<tr>
<td>Site Exposure</td>
<td>Describes the level of exposure on the site.</td>
<td>Normal, Sheltered, exposed etc.</td>
<td>Name</td>
</tr>
<tr>
<td>Blind</td>
<td>Either the name of a 24hr</td>
<td>“9to5”, “Constant”</td>
<td>Text or</td>
</tr>
<tr>
<td>Control</td>
<td>Description</td>
<td>Value/Unit</td>
<td></td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------</td>
<td>--------------------</td>
<td></td>
</tr>
<tr>
<td>Shade Factors</td>
<td>The upper and lower shading due to plants and banners etc (0-1).</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Vent Profile</td>
<td>Name of 24hr Profile of percentages of vent closure</td>
<td>“9to5”, “Constant”</td>
<td></td>
</tr>
<tr>
<td>Vent area</td>
<td>Area of upper and lower vents</td>
<td>5.2 (m²)</td>
<td></td>
</tr>
<tr>
<td>Vent separation</td>
<td>Distance between upper and lower vents</td>
<td>15.9 (m)</td>
<td></td>
</tr>
<tr>
<td>Percentage Leakage</td>
<td>The percentage of area that leaks when the vent is closed.</td>
<td>3%</td>
<td></td>
</tr>
<tr>
<td>Coefficient Performance</td>
<td>A CP value (0-1) for each façade orientation in 45 degree steps</td>
<td>N: 0, NE: 0.2, E:0.4 etc</td>
<td></td>
</tr>
<tr>
<td>Type of Plant</td>
<td>Type of plant used to condition the space</td>
<td>“Mechanical Ventilation”, “Room Unit”</td>
<td></td>
</tr>
<tr>
<td>Mechanical Vent Air Source</td>
<td>If mechanically ventilated then this defines the type of air supplied.</td>
<td>“Outside”, “scheduled” or “Extract”</td>
<td></td>
</tr>
<tr>
<td>Flow Rate</td>
<td>Mech. Vent rate in volumes per second</td>
<td>1.9 (m³/sec)</td>
<td></td>
</tr>
<tr>
<td>Flow rate Profile</td>
<td>Name of the profile applied to the flow rate.</td>
<td>“Constant” etc</td>
<td></td>
</tr>
<tr>
<td>Supply Temperature</td>
<td>Base temperature of the supply air</td>
<td>16 (°C)</td>
<td></td>
</tr>
<tr>
<td>Swing</td>
<td>The number of degrees by which the base temperature fluctuates</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>Supply Temp. Profile</td>
<td>Name of the profile applied to the Swing around the base temperature</td>
<td>“9to5”, “Constant”</td>
<td></td>
</tr>
<tr>
<td>Maximum Heating Duty</td>
<td>The plants capacity to heat</td>
<td>120.0 (Kw)</td>
<td></td>
</tr>
<tr>
<td>Maximum Cooling Duty</td>
<td>The plants capacity to cool</td>
<td>155.5 (Kw)</td>
<td></td>
</tr>
<tr>
<td>Proportional Band</td>
<td>Plants control band in degrees Kelvin</td>
<td>3k</td>
<td></td>
</tr>
<tr>
<td>RH Set point</td>
<td>Percentage Relative Humidity set point.</td>
<td>54%</td>
<td></td>
</tr>
<tr>
<td>RH Proportional design</td>
<td>The band either side of the set point in which the RH is controlled.</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Efficiency</td>
<td>Percentage efficiency of the</td>
<td>85%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Description</td>
<td>Example</td>
<td>Type</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>----------------------------------------------</td>
<td>--------------------</td>
</tr>
<tr>
<td>Rest Days</td>
<td>Days of the week the space is un-occupied</td>
<td>Monday, Tuesday ..</td>
<td>Cyclic-grade</td>
</tr>
<tr>
<td>Conditioned on Rest days</td>
<td>Flag which specifies if the space was conditioned on rest days.</td>
<td>Yes/No or True/False</td>
<td>Binary</td>
</tr>
<tr>
<td>Plant Profiles</td>
<td>Name of the profile of plant usage on normal and rest days.</td>
<td>“9to5”, “Constant”</td>
<td>Name</td>
</tr>
<tr>
<td>First day of Month</td>
<td>The first day of the month being analysed</td>
<td>Monday, Tuesday ……</td>
<td>Cyclic-grade</td>
</tr>
<tr>
<td>Day</td>
<td>Day of the month used for full analysis output.</td>
<td>15</td>
<td>Cyclic-grade</td>
</tr>
<tr>
<td>Hour (from and to)</td>
<td>24x Hour of the day. Specified by a start and finish hour.</td>
<td>0 to 1, 1 to 2… 23 to 24</td>
<td>2x Cyclic-grade</td>
</tr>
</tbody>
</table>

The following values are given for each hour of the above

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Example</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ext. Dry bulb Temp.</td>
<td>Dry bulb temp. of the outside air</td>
<td>10 (°C)</td>
<td>Balance</td>
</tr>
<tr>
<td>Int. lower Dry bulb Temp.</td>
<td>Dry bulb temp. of the space (lower region)</td>
<td>22 (°C)</td>
<td>Balance</td>
</tr>
<tr>
<td>Int. Dry Res Temp.</td>
<td>Dry resultant temp. of the space</td>
<td>21.2 (°C)</td>
<td>Balance</td>
</tr>
<tr>
<td>Int. upper Dry bulb Temp.</td>
<td>Dry bulb temp. of the space (upper region)</td>
<td>24.5 (°C)</td>
<td>Balance</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>Percentage relative humidity of the space</td>
<td>55%</td>
<td>Percentage</td>
</tr>
<tr>
<td>Ventilation ACH</td>
<td>Ventilation rate in air changes per hour</td>
<td>2.5</td>
<td>Amount</td>
</tr>
<tr>
<td>Ventilation Rate</td>
<td>Ventilation rate in volumes per second</td>
<td>0.09 (m³/sec)</td>
<td>Amount</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>Speed of wind used for natural ventilation</td>
<td>4 (m/s)</td>
<td>Amount</td>
</tr>
<tr>
<td>CP Difference</td>
<td>Pressure Coefficient difference used for natural ventilation.</td>
<td>0.2</td>
<td>Balance</td>
</tr>
<tr>
<td>Supply air temp.</td>
<td>Temperature of any air supplied to the space, maybe none.</td>
<td>12 (°C) or “None”.</td>
<td>Balance or Text</td>
</tr>
<tr>
<td>Sensible Load</td>
<td>Sensible load on the space</td>
<td>12 (Kw)</td>
<td>Amount</td>
</tr>
<tr>
<td>Ext. Wet Bulb Temp.</td>
<td>External wet bulb air temperature</td>
<td>18.3 (°C)</td>
<td>Balance</td>
</tr>
<tr>
<td>Ext. Moisture Content</td>
<td>Content of moisture in the outside air.</td>
<td>18 (g/Kg)</td>
<td>Amount</td>
</tr>
</tbody>
</table>
### The Application of Visualisation Techniques to the Process of Building Performance Analysis

<table>
<thead>
<tr>
<th>Ext. Perc. Saturation</th>
<th>Percentage saturation of outside air.</th>
<th>76%</th>
<th>Percentage</th>
</tr>
</thead>
</table>

**END**

<table>
<thead>
<tr>
<th>Posture</th>
<th>Posture of person used for comfort calculation</th>
<th>Standing, Seated etc.</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of analysis plane</td>
<td>Height above floor of the analysis plane</td>
<td>1.0 (m)</td>
<td>Amount</td>
</tr>
<tr>
<td>Activity Level</td>
<td>Activity level of person used for comfort analysis</td>
<td>Walking Fast etc</td>
<td>Name</td>
</tr>
<tr>
<td>Clothing Level</td>
<td>Clothing level of person used for comfort analysis</td>
<td>Light office wear</td>
<td>Name</td>
</tr>
<tr>
<td>Plant Type</td>
<td>Type of plant used for comfort analysis</td>
<td>Natural ventilation</td>
<td>Name</td>
</tr>
<tr>
<td>Air velocity</td>
<td>Velocity of air within the space</td>
<td>0.3 (m/s)</td>
<td>Amount</td>
</tr>
<tr>
<td>Shade Factor</td>
<td>Factor applied to adjust shading levels for comfort analysis.</td>
<td>0.1</td>
<td>Proportion</td>
</tr>
<tr>
<td>Time</td>
<td>Hour 1 to 24 of the result.</td>
<td>1, 2, 3 … 24</td>
<td>Cyclic-grade</td>
</tr>
<tr>
<td>PMV</td>
<td>Predicted Mean Vote for each Time step</td>
<td>-1.3</td>
<td>Cyclic-balance</td>
</tr>
<tr>
<td>PPD</td>
<td>Percentage People Dissatisfied for each Time step</td>
<td>12%</td>
<td>Percentage</td>
</tr>
<tr>
<td>MRT</td>
<td>Mean Radiant Temperature for each Time step</td>
<td>36 (°C)</td>
<td>Balance</td>
</tr>
<tr>
<td>Hour (from and to)</td>
<td>24x Hour of the day. Specified by a start and finish hour.</td>
<td>0 to 1, 1 to 2… 23 to 24</td>
<td>2x Cyclic-grade</td>
</tr>
</tbody>
</table>

**The following values are given for each hour of the above**

| Effective Vent Area | The effective area of the combined vents | 2.35 (m²) | Amount |
| Mech. Vent. Rate | Mechanical ventilation rate in volumes per second | 0.89 (m³/sec) | Amount |
| Total Sensible Gain | Total sensible gain to the space per square area of the spaces floor. | 150 (w/m²) | Amount |
| Individual sensible gains | Sensible gains to the space (for each) per square area of the spaces floor. | 52 (w/m²) | Amount |
| Total Latent Gain | Total Latent gain to the space per square area of the spaces floor. | 150 (w/m²) | Amount |
| Equipment & Occupant latent gains | Latent gains to the space (for each) per square area of the spaces floor. | 52 (w/m²) | Amount |

**END**

| Total Num. Surfaces | Total number of surfaces in the space | 9 | Count |

**The following values are given for each of the surfaces above**

<p>| Surface Number | Surface identifier | 13 | Text |</p>
<table>
<thead>
<tr>
<th>Surface Type</th>
<th>Connects to 4, Wall (int), Wall (ext) or Window in 4</th>
<th>Text</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glazed</td>
<td>Identifies if the surface is glazed or not</td>
<td>Yes/No or True/False Binary</td>
</tr>
<tr>
<td>Orientation</td>
<td>Orientation of the surface from North.</td>
<td>15 Degrees Cyclic-grade</td>
</tr>
<tr>
<td>Tilt</td>
<td>Tilt of the surface from horizontal. 0 = floor, 90 = wall and 180 = ceiling.</td>
<td>110 Degrees Cyclic-grade</td>
</tr>
<tr>
<td>Area</td>
<td>Area of surface.</td>
<td>23 (m²) Amount</td>
</tr>
<tr>
<td>Shade Profile</td>
<td>Name of the 24hr % profile used for shading.</td>
<td>“Morning”, “BigBuilding” Name</td>
</tr>
<tr>
<td>Heat Trans. Coef.</td>
<td>Heat Transfer Coefficients for inner and outer surfaces</td>
<td>17.8 Amount</td>
</tr>
<tr>
<td>Surface Temperature</td>
<td>Internal temperature of surface</td>
<td>23.9 (°C) Balance</td>
</tr>
</tbody>
</table>

END

| Num Opaque Surfs. | Number of opaque surfaces in the space | 6 Count |

The following values are given for each of the opaque surfaces above

| Heat Transfer Temperature | Heat transfer temperature for each Opaque surface at each Time step | 13.6 (°C) Balance |

END

| Num of Glazed Surfs. | Number of glazed surfaces in the space | 3 Count |

The following values are given for each of the glazed surfaces above

| Solar Gain | Solar gain (direct and diffuse) per unit area of each translucent Surface at each Time step | 46 (w/m²) Amount |
| Retransmitted Solar Gain | Solar gain retransmitted from the space per unit area of each translucent Surface at each Time step | 46 (w/m²) Amount |

END

EOF End of File flag

Note: All data classifications except Ranks and Counted-fractions identified in ROOM output data.

3.0 User profiles

The following six profiles were generated by the task analysis.
The Application of Visualisation Techniques to the Process of Building Performance Analysis

### User 1

<table>
<thead>
<tr>
<th>Occupation.</th>
<th>Senior HVAC Engineer.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of analysis</td>
<td>Daily.</td>
</tr>
<tr>
<td>Purpose of analysis</td>
<td>To optimise a design. Trying to understand a problem and solve it. Examples given include evaluation of glazing and façade options.</td>
</tr>
<tr>
<td>Quantity of analysis</td>
<td>Approx. ten runs each producing more than 100,000 numbers.</td>
</tr>
<tr>
<td>Formats used for representation</td>
<td>Spreadsheets, two/three-dimensional graphics, virtual environments and animations/videos.</td>
</tr>
<tr>
<td>Used for</td>
<td>Optimisation and presentation to colleagues of the same discipline.</td>
</tr>
</tbody>
</table>

**Result Validation**

| Work flow | A steady state hand heat balance is calculated with the aid of a spreadsheet. The resulting air temperature is compared with the thermal analysis. This is used to indicate the sensitivity of the space. Further sensitivity analysis are performed using thermal analysis tools which ultimately define the CFD boundary conditions. |
| Activities | Hand calculations, thermal analysis then CFD. Summary e-mail sent to project team to confirm inputs. |
| Results | When satisfied with the model or modelling is abandoned. |
| Data sets | Absorbed and transmitted solar radiation as well as many others. |
| Errors | Mathematical and unit conversion errors. Small errors are hard to identify yourself so independent checking is required. These occur due to the amount of disparate input that is hard to review simultaneously. These may cause large errors, not necessarily in the base case but the conclusions drawn from the analysis. |
| Problems Identified | Thermal sensitivity analysis is quick to perform but produces too much data. Steady stat calculations take longer but the output is easy to compare. Biggest problem is the translation and communication of information between the project and the simulation team. Rules of thumb define targets, with lots of input they don’t give guidance on whether you are modelling appropriately or not. |

**Results Analysis**

| Work flow | With everything fixed a single design variable is altered. Low level dry bulb temperature (over the occupied period) is often the focus of the study. If unfavourable then check the ceiling and floor temperature make sense for the corresponding resultant temperature. |
| Activities | Standard graphs produced, extra graphs produced only when necessary. Air Temp – comparisons, optima, trends, relationship with other temperatures and ventilation rates. |
| Results | Optimum system identified. |
| Data sets | Dry bulb and resultant temperatures. |
| Errors | Information recorded during each stage for QA and peer review purposes, this helps identify any errors. |
Result Presentation

Overview

Technical reports consist of: background (what you did), discussion (the impact and what the results mean), summary (key discussion points) & recommendations (how to proceed). Results often summarised in emails for internal reviews. If selling a solution then graphics are required.

Data sets

Ventilation areas and corresponding air change rates. Temperature.

Techniques

Line charts and tables. Charts compare one variable for each change in a design parameter. Multiple CFD images are placed on the same page with descriptive text close by. Guidance on result interpretation is also included.

Problems Identified

Line charts become confusing when two parameters are changed together. In thermal modelling it is harder to get a wow factor than on CFD as people don’t tend to get infused by line charts as much as coloured cross-sections. CFD colour scales can be misleading to non experts (e.g. 18°C coded in red).

Examples

The CFD predictions are shown as contour plots on various vertical sections within the auditorium and over the occupied zones. In addition, particle traces are used to map the air movement. Each plot includes its own scale indicating the magnitude of an environmental variable at a particular point. Air temperature is shown in °C and air velocity in m/s. [generated using StarCD].

The air velocity distribution on a vertical section through the centre of the seating areas. Shows the increased velocities in the dome, in particular close to the supply nozzles, and extract regions.

Summary or results:

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean velocity in occupied zones</td>
<td>0.075</td>
<td>0.072</td>
</tr>
<tr>
<td>Mean temperature in the stalls occupied zone</td>
<td>25.4</td>
<td>22.4</td>
</tr>
<tr>
<td>Mean temperature in occupied zones excl. the orchestra pit</td>
<td>23.5</td>
<td>22.3</td>
</tr>
<tr>
<td>Mean temperature in full volume</td>
<td>21.0</td>
<td>20.0</td>
</tr>
</tbody>
</table>

The air movement with temperatures towards the dress circle extract. The twisting is almost non-existent with warm air being drawn from lower level in the auditorium.
### User 2

<table>
<thead>
<tr>
<th><strong>Occupation.</strong></th>
<th>Graduate HVAC Engineer.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency of analysis</strong></td>
<td>More than once a week.</td>
</tr>
<tr>
<td><strong>Purpose of analysis</strong></td>
<td>To optimise a design and understand how it works as well to size features of the building.</td>
</tr>
<tr>
<td><strong>Quantity of analysis</strong></td>
<td>Approx. 25 runs each producing approximately 10,000 numbers.</td>
</tr>
<tr>
<td><strong>Formats used for representation</strong></td>
<td>Tables, Spreadsheets, two and three-dimensional graphs.</td>
</tr>
<tr>
<td><strong>Used for</strong></td>
<td>Improving the understanding of a problem.</td>
</tr>
</tbody>
</table>

#### Result Validation

**Work flow**
Develop an idea of expected system performance using an additional piece of software, experience or hand calculation. Check min & maximum values (tabular). Perform quick visual check of several parameters. Peer review.

**Activities**
Peer review with senior engineer: Important input summarised in tables and presented alongside graphical results (temperature over time, cooling loads etc). Solar gains – Comparison, Maximums, trends, calcs. & relationships inc. spatial. Internal Temp – Comparison, optima, trends & relationships inc. spatial. Elements – Comparison (with old results), relationships inc. spatial & distinguish.

**Results**
Problems identified by freak results i.e. the absence of patterns that are expected. For example internal loads driven by occupancy and solar gains.

**Data sets**
Loads, Airflow, supply air temperature

**Errors**
Forget to set certain input. Some errors identified watching the run time graph. Would be reduced by a clearly laid out set of data for peer reviews.

**Problems Identified**
Things like surface elements aren’t in the results and are hard to check without visual aids and clear descriptions. Systems are harder to validate due to the number of variables. Easy to switch on functions without knowledge of effects. Difficult to manage a dozen cases with different variations of input data.

#### Results Analysis

**Work flow**
Produce tables and graphs (based on a template). Model used to check designs dynamics, if desired results not achieved then the model is NOT tweaked. Boiler sizing done by other methods but analysis used to confirm dynamic effects are not excessive.

**Activities**
Produce standard base case (often insufficient for criteria) then analyse variations e.g. DG, DG + blinds * high performance glass + coatings. Comparisons built progressively as new results are available.

**Results**
Graphs of internal temperatures and sometimes solar gains – for occupied period.
Data sets | Temperature, solar gains and heating/cooling load.
---|---
Errors | Because you don’t progress through the stages of analysis in fluent steps.
Problems Identified | Not a great fan in comfort (clients like it and it’s more intuitive to present differences in satisfaction) as it’s not realistic (no occupant adaptation).

**Result Presentation**

| Overview | Prepare simple reports for senior engineers and clients
| Data sets | Internal temperature etc.
| | Min, max, mean and standard deviation of variables.
| Techniques | Keep things simple and clear (plus colourful). Single chart of variables being compared (plus external condition). This is accompanied by text and tables based on the results. Format/content of presentation depends on paper size.
| Problems Identified | Black and white printing of colour charts not so much of a problem as reports now issued in pdf format.

**Examples**

The following image was generated using Flowvent
### User 3

<table>
<thead>
<tr>
<th>Occupation</th>
<th>Senior HVAC Engineer.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of analysis</td>
<td>More than once a month.</td>
</tr>
<tr>
<td>Purpose of analysis</td>
<td>Natural ventilation and summer overheating checks. Feasibility studies of limited cooling systems. Part L compliance check.</td>
</tr>
<tr>
<td>Quantity of analysis</td>
<td>Conducts 25 runs producing more than 10,000 numbers each.</td>
</tr>
<tr>
<td>Formats used for representation</td>
<td>Spreadsheets.</td>
</tr>
<tr>
<td>Used for</td>
<td>To give the client an idea of the proposed designs performance, advise whether this is acceptable and optimise the design.</td>
</tr>
</tbody>
</table>

#### Result Validation

**Work flow**
Check fabric u-values against architects’ specification. Use diagrams to check models geometry. Check temperatures, air change rates and solar gains (sometimes broken down to individual windows). Automatic graphs used to quickly check all the output – useful for identifying trends.

**Activities**
Air changes – Comparisons, optima, relationships inc. spatial & calculations.
Heat Gains - Comparisons, optima, relationships & spatial relationships.
Solar Gains - Comparisons, optima, relationships inc. spatial & calculations.

**Results**
Confidence in model and analysis engine is gained after varying the inputs sufficiently.

**Data sets**
Temperature, solar gains, solar gains per window, load profiles and ACH

**Errors**
Load profiles often don’t reflect the desired values, shading coefficients wrongly applied & problems with blinds.

#### Results Analysis

**Work flow**
External shading and solar coated glass studies are based on sensitivity analysis (typically 3 or 4 runs). A simple base case is used as a starting point – this is the validated model. Cases might include two different shading options and a solar glass option.

**Activities**
Divide each windows solar gain by it’s respective area to identify potentially large heat sources. Stacked bar charts are produced using the individual windows.

**Results**
Happy with the data produced.

**Data sets**
Solar gains, gains per window. PPD is used alongside temperature to gain the overall picture of the spaces performance.

**Errors**
The windows orientation and tilt is confusing, so is the notation used (e.g. window 3 in wall 23). Also input errors occur with thermal boundaries.

**Problems Identified**
Defining profiles. Difficult to check the location of LowE coatings

#### Result Presentation

**Overview**
Typically a short report is produced including a picture of the model, summary of input/weather data and then the results. Each analysis is
<table>
<thead>
<tr>
<th><strong>Support Material</strong></th>
<th>presented on a separate sheet of paper. Also presented at design meetings using the same sheets.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data sets</strong></td>
<td>Solar loads, temperatures and PPD.</td>
</tr>
<tr>
<td><strong>Techniques</strong></td>
<td>Print the months’ weather data and highlight the chosen day.</td>
</tr>
<tr>
<td><strong>Problems Identified</strong></td>
<td>Cautious of using thermal analysis tool for ventilation studies because of the unknowns involved e.g. vent locations.</td>
</tr>
</tbody>
</table>

**Examples**

A stacked bar chart used to indicate the components of internal load. Useful for indicating the presences of individual components but not their comparison (as they start at different y positions).

![Stacked bar chart](image)

**fig(C2) internal gains to dwelling over 24 hours for winter design day**

A screenshot from the analysis program is used to show the models geometry, location of windows and size of shading devices.

![Screenshot of analysis program](image)
User 4

<table>
<thead>
<tr>
<th>Occupation</th>
<th>HVAC Engineer.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of analysis</td>
<td>More than once a week.</td>
</tr>
<tr>
<td>Purpose of analysis</td>
<td>To check the feasibility of a design. Typically when standard software is inadequate in someway.</td>
</tr>
<tr>
<td>Quantity of analysis</td>
<td>One run producing more than 100,000 numbers.</td>
</tr>
<tr>
<td>Formats used for representation</td>
<td>Spreadsheets, two-dimensional graphics and animations/videos.</td>
</tr>
<tr>
<td>Used for</td>
<td>Communication with external clients familiar with the subject.</td>
</tr>
</tbody>
</table>

**Result Validation**

<table>
<thead>
<tr>
<th>Work flow</th>
<th>Double check the input. Peer review of input. Skim read results, looking for unexpected building response. Sensitivity analysis: set up a table of options based on important variables (project specific).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activities</td>
<td>Inspect results which are easy to graph. Air temp. - Comparison, optima, relationship (with input) &amp; spatial (if stratified). ACH - Optima (related to threshold), trends, relationship &amp; spatial relationship.</td>
</tr>
<tr>
<td>Results</td>
<td>Process concludes when satisfied with the models response (no surprise values).</td>
</tr>
<tr>
<td>Data sets</td>
<td>Sensitivity studies use air temperature, change rate and MRT. Unexpected MRT values may lead to the inspection of surface temperatures or gains to the space.</td>
</tr>
<tr>
<td>Errors</td>
<td>Often identified after a period away from the model, can be hard to spot as some input errors have little influence on the models output.</td>
</tr>
<tr>
<td>Problems Identified</td>
<td>The input is distributed amongst many tables making it difficult to spot errors, some input is even forgotten.</td>
</tr>
</tbody>
</table>

**Results Analysis**

<table>
<thead>
<tr>
<th>Work flow</th>
<th>Compared results with design limits and calculated the standard deviation. Of the 25 cases examined only three were presented to the client.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activities</td>
<td>Compare output using min, max, mean and SD – gives an indication of stability. Plotted temperature and humidity trends (for 10th year).</td>
</tr>
<tr>
<td>Results</td>
<td>Ran multiple cases and identified important variables. Successful systems were reported by another engineer.</td>
</tr>
<tr>
<td>Data sets</td>
<td>Between 1 and 10 years long.</td>
</tr>
<tr>
<td>Errors</td>
<td>Mistakes found in humidity controller during sensitivity analysis i.e. increasing air flow had opposite effect.</td>
</tr>
<tr>
<td>Problems Identified</td>
<td>Couldn’t compare multiple RH plots on the same graph as the ‘noisy’ data from one series obscures the other. The most sensible objective for the analysis isn’t always what people want to hear or see.</td>
</tr>
</tbody>
</table>
### Result Presentation

<table>
<thead>
<tr>
<th><strong>Overview</strong></th>
<th>Prepared table of results accompanied with an explanation of the significance of each value/trend. Prepared graph of RH (showing it in limits)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data sets</strong></td>
<td>Temperature and RH.</td>
</tr>
<tr>
<td><strong>Techniques</strong></td>
<td>Tables &amp; Graphs. Graphs compare either multiple datasets or multiple variables. They also include legends, colour coding and an indication of the design limits.</td>
</tr>
<tr>
<td><strong>Problems Identified</strong></td>
<td>The idea had already been ‘sold’ so the analysis was a post rationalisation.</td>
</tr>
</tbody>
</table>

### Examples

Taken from passive archive building physics analysis.

**Figure 3. Average Temperature Comparisons**

The order of the legend makes it difficult to read lines (which have a similar colour when printed). Legend terminology confusing.

**Figure 5. Spot Relative Humidity Comparisons**

Placing a two line legend at the bottom of the graph may have increased the graph size (for the same screen area).

**Figure 10. Conditions and Predicted Internal Conditions for a Full Year of Weather Data**

Good example of system performance. Shows four variables over a year with design limits.
User 5

<table>
<thead>
<tr>
<th>Occupation.</th>
<th>Graduate HVAC Engineer.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of analysis</td>
<td>More than once a week.</td>
</tr>
<tr>
<td>Purpose of analysis</td>
<td>Used to size building elements (peak heat gains and losses) and understand overall building performance (including comfort – which is easy to check). Most suitable tool for the required calculations and considered faster than by hand.</td>
</tr>
<tr>
<td>Quantity of analysis</td>
<td>Approx. ten runs each producing up to 100 numbers.</td>
</tr>
<tr>
<td>Formats used for representation</td>
<td>Spreadsheets, two/three-dimensional graphics, virtual environments and animations/videos.</td>
</tr>
<tr>
<td>Used for</td>
<td>Communication with external clients unfamiliar with the subject</td>
</tr>
</tbody>
</table>

Result Validation

**Work flow**

Use design guides to check input. Perform one analysis and check: 1) overall watts/m² for sizing cases. 2) Solar load – based on input and glazing types. 3) if set has been met. 4) Maybe a peer review. If the analysis focused on high performance glazing then run the model with single glazing for comparison.

**Activities**

For natural ventilation studies an analysis of one months data would be used to identify hot/cold periods.

Plant load – Comparison, Optima, trends, relationships and calculations.

Solar load – Comparison, Optima, trends, relationships inc spatial & calculations.

Temperatures – Comparison, Optima, trends & relationships.

ACH – Comparison, Optima, trends & relationships.

**Results**

Happy with model

**Data sets**

Weather data, Solar load, temperature data and air change rate.

**Errors**

Not if all the input is correct – inhouse software is validated. Input errors include windows in internal surfaces.

**Problems Identified**

Different versions of the same analytical tool often produce different results.

Result Analysis – Plant sizing

**Work flow**

Determine peak heating cooling loads, post process (e.g. add latent load), add an error margin and select plant. Generally only one analysis but may change occupancy to see impact.

**Activities**

Think about what plant is to be used so you know how the results are to be used. Plant loads – Optima, trends (response time) and calculation (of averages).

**Results**

A plant size which is used with the manufacturers data to specify equipment.

**Errors**

If you change the input then you must redo the post processing, getting this out of synch results in errors.

**Problems Identified**

When doing a very large number of analysis it is sometimes necessary to interpolate answers.
Results Analysis – Natural Ventilation

**Work flow**
Set a base case which is normally a combined vent area of 5% of the floor area. Analyse the effect of input parameters on the internal air temperature over the occupied period.

**Activities**
Looking as the effects of vent sizes, vent profiles, night cooling etc. Dry resultant used as a gauge of internal temperature.

**Data Sets**
Trends of internal temp over the day.
Relationship between ACH, external and internal temperature.
Interested in maximums or high averages of resultant temperature.
Spatial relationship between vent size and location.

**Results**
Comparison of options and comfort calculations (for client use).

**Problems Identified**
The definition of natural ventilation areas and locations is vague, not sure when they are and where the air goes.

**Result Presentation – Sizing (S), Natural ventilation (N) & Comfort (C)**

**Overview**
S) Sizing results not reported unless they were a comparison of options.
N) Natural ventilation is reported as performance over time and effects of usage.
C) Produce comfort plots.

**Techniques**
S) Two systems would be compared using a text description, five systems in a bar chart. Stacked bar charts not used – separate heating and cooling graphs.
N) An s-curve of the number of occurrences at a given temperature over time – the heating and cooling periods are identified.
C) Comfort plot with expanded legend explaining the meaning.

**Problems Identified**
All axis must be kept on the same scale. Ventilation rate is not presented as there is doubts on how valid it is.
C) it only really shows the effects of solar gains (i.e. the effects of windows).

**Examples**

Indicates difference in comfort (PPD) due to changing the roof panel construction.
User 6

<table>
<thead>
<tr>
<th>Occupation</th>
<th>Graduate HVAC Engineer.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of analysis</td>
<td>More than once a month.</td>
</tr>
<tr>
<td>Purpose of analysis</td>
<td>To optimise a design and understand how it works. Typically checking thermal performance/comfort &amp; sizing heating equipment.</td>
</tr>
<tr>
<td>Quantity of analysis</td>
<td>Ten runs producing up to 1,000 numbers each.</td>
</tr>
<tr>
<td>Formats used for representation</td>
<td>Spreadsheets, two-dimensional and three-dimensional graphs.</td>
</tr>
<tr>
<td>Used for</td>
<td>Communication with ext. clients unfamiliar with the subject.</td>
</tr>
</tbody>
</table>

Result Validation

<table>
<thead>
<tr>
<th>Work flow</th>
<th>Simple hand calculation ($Q = U A \Delta T$). Sensitivity analysis (printing the results each time).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activities</td>
<td>Focus of the study was to reduce the 24hr average internal temperature above 19.5 Degrees C by adjusting window size and glazing type. Internal dry bulb – Optima, 24hr Average calculation and spatial relationship.</td>
</tr>
<tr>
<td>Results</td>
<td>Rolling process of validation and design.</td>
</tr>
<tr>
<td>Data sets</td>
<td>Internal dry bulb and solar gains</td>
</tr>
<tr>
<td>Errors</td>
<td>During sensitivity analysis it is easy to forget to reset variables.</td>
</tr>
<tr>
<td>Problems Identified</td>
<td>It easy to become entrenched in the process – not knowing when to stop. Had to change the model based on design decisions early on in the validation process because people wanted results quickly.</td>
</tr>
</tbody>
</table>

Results Analysis

<table>
<thead>
<tr>
<th>Work flow</th>
<th>Produce new options (based on physical/practical restraints), analyse them and prepare a bar chart of results (including a base case). The new options were decided in the order that least affected the architecture.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activities</td>
<td>Each parameter studied in isolation, if the desired conditions were not met then cumulative effects were studied.</td>
</tr>
<tr>
<td>Results</td>
<td>A design which maintained the required conditions.</td>
</tr>
<tr>
<td>Data sets</td>
<td>Internal dry bulb and its average plus solar gains</td>
</tr>
<tr>
<td>Errors</td>
<td>The whole flat was modelled as a single space.</td>
</tr>
<tr>
<td>Problems Identified</td>
<td>Wasn’t able to adequately model the sunspace on the exterior of the flat. Models response reliant on internal gains which were fairly undefined.</td>
</tr>
</tbody>
</table>

Result Presentation

<table>
<thead>
<tr>
<th>Overview</th>
<th>Options repeatedly presented to the architect who was located within the same office.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data sets</td>
<td>Internal dry bulb temperature and its’ 24 hour average.</td>
</tr>
<tr>
<td>Techniques</td>
<td>Bar charts of average temperatures including a legend and option number. Used an overview (picture and line chart) of the model to justify some of the demands that were placed on the architecture.</td>
</tr>
<tr>
<td>Problems Identified</td>
<td>Tables took longer to produce than bar charts and so weren’t used. Like more control over the appearance of the Excel graphs.</td>
</tr>
</tbody>
</table>
Examples

Bar chart with an unnecessary legend and badly formatted x axis labels. Tables not used as they took longer to create.

An alternative representation using the same screen area but with clearer labels and greater chart resolution.
4.0 Final Prototype Evaluation: Questionnaire

Your name:  

1) When did you use the prototype (place an X in one box):

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>I didn’t</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Once, when it was installed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>When I had a problem with Room data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Every time I used Room</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other, State below</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2) Did you (place an X under Yes or No)?

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>A - Explore the interface</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B - Look at existing project data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C - Use it on a live project</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D - Use it to generate images for reports/presentations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E - Show it to anyone else</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F - Discover new information from your data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G - Discover problems in your data</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3) Did you use all the function/tabs (place an X in one box)?

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>YES</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO, State reason below</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4) Please rate the usefulness of each tab from 1 to 5 where 1 = ‘not at all useful’ and 5 = ‘very useful’ (please put 0 if tab not used)?

<table>
<thead>
<tr>
<th></th>
<th>Files</th>
<th>Overview</th>
<th>Result Analysis</th>
<th>Result Comparison</th>
<th>3D View</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5) What is the worst thing about the prototype?

Continued on next page…
6) If you had your *existing tools* (Edeta, Room, Excel etc) AND the *prototype* which tool/function would you use to do each of the following:

<table>
<thead>
<tr>
<th>Task</th>
<th>Tool Name</th>
<th>Function/Tab</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A</strong> - Check the input has been entered correctly.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>B</strong> - Obtain an overview of the analytical data.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>C</strong> - Present the analytical data in a peer review.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>D</strong> - Understand the influences on the results to changes in geometry.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>E</strong> - Compare results of multiple analysis.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7) How do you rate the prototype as a tool for visualising building performance data (Please highlight **one option**)?

Very poor / Slightly poor / Average / Slightly good / Very good

8) Would you be happy if the prototype was uninstalled and not replaced (Please highlight **one option**)?

Yes / No / Maybe

9) Please highlight the option that best describes your agreement to the statement:  
   “The prototype improved the accuracy and efficiency of my data interpretation”

Strongly disagree / Slightly disagree / Neutral / Slightly agree / Strongly agree

10) Is there anything missing from the prototype?

11) Any other comments?

Thank You for your help.

Please email this document and the RoomViz log file called monitor.txt (located in C:\Program Files\InfoDev\RoomViz) to matthew.pilgrim@arup.com