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COMMUNICATING BUILDING SIMULATION OUTPUTS TO USERS

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ABSTRACT

Copious amounts of data are generated by contemporary building simulation (BS) programs and the translation of these data to information that may be acted upon is problematic. Although graphs are an effective way of displaying quantitative information, they are unable to support experiential appraisals whereby building performance can be fully comprehended. To achieve this requires the use of multimedia techniques, including colour, sound and animation. This paper reports the interim results from a PhD project that is developing a Web-enabled program to assist in the interpretation of the performance trends inherent in large data sets as produced by BS programs. The aim is to identify and link key performance concepts and support an inter-comparison of alternative design hypotheses.

INTRODUCTION

Few studies have examined the problematic issue of communicating BS results effectively, efficiently and flexibly to users such as designers, energy managers and policy makers. The predicament for such users is that simulation can generate vast quantities of performance data that are both time varying and inter-related in a complex way.

A study by Haberl *et al* (1998) demonstrated that two graphical indices can be used to help a user to efficiently analyse hourly performance data, check for errors and establish trends over an extended time period. Another study (Clarke *et al*. 1996, 1997) proposed the concept of an Integrated Performance View (IPV) whereby a range of relevant performance indicators is collated to represent the multi-variant performance of a building. Such studies share a common deficiency: the results are presented in a static manner that depends on the program developer's perception of what is required.

The research reported in this paper accepts the IPV concept as its starting point. The approach is then deepened and cognition rules are added in order to ensure that the presented information conveys the building's performance state in a manner that addresses the needs of the possible user types. The aim of the research is to investigate the applicability and usefulness of cognition rules and data perceptualisation techniques within a computational approach to design.

The paper commences with the results from a literature review relating to cognition and perceptualisation rules. A new software tool, which is under development, is then described. This tool is being used to test the applicability in practice of alternative approaches to information presentation.

DATA DISPLAY BEST PRACTICE

Data can be displayed in a variety of ways (e.g. tables, graphs, animations *etc*), with each approach offering sub-set possibilities (e.g. histograms, pie charts and line profiles in the case of a graphical display). Furthermore, sub-sets may have features such as three-dimensionality, colour and sound. The aim of the present work is to explore techniques for displaying complex building performance data that assists with the ready assimilation of the inherent 'message'.

Taken together, human senses give rise to perceptualisation, including visualisation, sonification, tactilisation and so on. According to Gleitman (1992), the smaller the Weber fraction the greater the sense modality. (The Weber fraction is defined as that ratio of 'stimulus intensity increment' over 'stimulus intensity' that produces a just-noticeable change.) The kinesthesis sense is the best way to detect a difference, followed by touch and then the auditory sense. Surprisingly, the least effective senses are vision and taste. Dix *et al* (1998) compared the reaction times of the auditory, visual and pain senses and demonstrated that the fastest reaction was associated with the auditory sense, followed by vision. He also demonstrated that combined signals result in more rapid response times.

From these findings it may be conjectured that in the context of building simulation, data visualisation alone should not be relied upon when attempting to convey performance differences between alternative design options.

Based on this literature review, the following guidelines for best practice in displaying data have been collated.

Graphical Display

In relation to graphical displays Tufte (1997) states:

> *"When we reason about quantitative evidence, certain methods for displaying and analyzing data are better than others; superior methods are more likely to produce truthful, credible, and precise findings. The difference between an excellent analysis and a faulty one can sometimes have momentous consequences."*

In other words, to be understood, graphics must first be accurately perceived (Cleveland 1985). The following compilation of graphics techniques has been provided by Tullis (1988).

Scatter − Shows how two continuous variables are correlated by depicting the distribution of points in two-dimensional space. Lines or curves may be superimposed to indicate trends. A variant technique, the bubble chart, allows the introduction of a third variable through the setting of a bubble's radius.

Line − Shows how two continuous variables are related, and highlights the changes in one variable over time. Where time is included, it is typically plotted on the horizontal axis. A third, discrete variable can be included using line-type or colour coding. Good practice is to use no more than four lines per graph, with each line having an associated label.

Area, band, strata or surface − these graphs may be used when several line graphs or curves represent the portions of a whole. The shared areas stacked on top of each other represent a category's contribution to the whole. The curve with the least variation should be located at the bottom of the graph to prevent the propagation of irregularities throughout the stacked curves. Each category (curve) should be labelled within its shaded area.

Bar, column or histograms – These show values of a single continuous variable for multiple separate entities, or for a variable sampled at discrete intervals. It is important to adopt a consistent orientation (horizontal or vertical) for related graphs. Spacing between adjacent bars should typically be less than the bar width to facilitate comparisons between bars. A useful variation is the deviation bar chart, in which bars are constructed so that, under normal conditions, the bar ends lie in a straight line.

Pie – This shows the distribution of data among parts that make up a whole. However, a bar or column chart will usually permit more accurate interpretation. Good practice is to limit the number of segments to 5 and to include the numeric value alongside the segment label.

Simulated meters – These show one value associated with one continuous variable. Where multiple values are to be displayed it is usually more effective to use bar charts or line graphs than multiple meters.

Star, circular or pattern – These show values of a continuous variable for multiple related entities. Values are displayed along spokes emanating from the origin. Different continuous variables may be represented if they are indexed so that the normal values of each variable can be connected to form an easily recognized polygon. This technique is useful for detecting patterns, but not for determining precise values or making accurate comparisons between variables.

3D − This device is useful when several variables are to be simultaneously displayed. In use, it is important to provide the user with an interactive rotation function. The augmentation of 2D data with 3D effects is not recommended (Tufte 1990):

> *"… simple and clear is better, extra ink is bad, and extraneous information detracts from the impact of graphics. Rendering uninformative depth is a bad idea in principle because it can lead to misperception of the information of interest, and it can hide the real content from the viewer."*

Maguire (1985) also considered the graphical coding of quantitative data and concluded that the graphical display of numerical data is an effective way to communicate trends, errors and breakdowns. Humans prefer graphical charts to tabulated text because the human perception system constantly seeks to find structure in order to understand the environment. Suggestions to improve the visual clarity of graphical charts include:

- clear labelling of axes and data;
- provision of grid lines to improve readability;
- differentiation of chart elements using colour or hatching; and
- the use of a logarithmic scale where the displayed data covers a wide range.

In relation to building simulation, four display techniques are apposite:

- bubble charts to depict correlations (e.g. cost versus benefit of design options);
- star charts to depict patterns (e.g. visual comfort and energy consumption as a function of design parameters);
- simulated meter charts to depict the change in a single parameter (e.g. daily temperature variation or energy cost); and

- bar/line charts to depict overall performance (e.g. thermal comfort, daylight availability *etc*).

Colour

Colour can structure and divide information and make it more pleasant to look at. Conversely, excessive use of colour results in colour pollution (Tufte 1990), which can seriously detract from the information content. Travis (1991) claimed that colour is useful to distinguish groups and to highlight prominent features. Davidoff (1987) suggested that colour is an effective segmentation device (i.e. areas that are related have the same or near-same colour) and that its use can assist searching operations (although too many colours increase search times). Colour, as a search-assisting agent, is more helpful to inexperienced users (when compared to black and white displays). Conversely, colour is less useful in categorisation and memorisation. The consistent use of colour to denote heating, cooling, and lighting energy demands, while clearly an effective device in BS, has yet to be standardised.

Sound

In relation to sound, Deatherage (1972) has reported that the message must be simple, short, deal with events in sequence, call for immediate action and be employed when the visual system of the user is overburdened. Further, the information conveyed must not be required at a later date.

The potential of sound in BS data display is immense. For example, when examining a large and complex data-set it is difficult to detect inherent problems or issues. Anomalies may be usefully flagged by an accompanying 'beep' to draw the user's attention to the issue and illicit action. Advanced uses of sound are also possible, for example to support an experiential appraisal of a room's acoustic behaviour.

3D Animation

Since humans inhabit a 3D environment, presenting information in 3D is appropriate. Such representations are particularly useful in a BS context because it allows models to be assessed from different viewpoints (Preece 1994). This provides an efficient mechanism to help detect model errors. Essentially, there are two methods to display 3D models, wire-frame and solid-object modelling. A wire-frame model comprises a line drawing from which the inside and outside cannot be differentiated. Such a model is useful for tasks in which surface structure is less important than internal structure. A solid-object model has a high degree of fidelity and lends itself well to the application of colour and shading. It therefore provides more information about the form of the object and is more useful for resolving ambiguities relating to shape. By enabling the user to distinguish between the inside and outside of an object, it presents less risk of misinterpretation and assists with accurate geometrical selections.

BS will obtain substantial benefit from the superimposition of performance data on a 3D building representation. For example, the representation of mould growth on the walls of a solid-object model, along with some key data, is more effective than a line graph depicting the surface temperature and relative humidity profiles from which mould growth potential may be inferred.

Animation is a powerful computer graphics technique in the BS context because it supports the conveyance of dynamic behaviour. Techniques such as accelerated time, zooming, panning and sequence editing are powerful devices to communicate complex information (Preece 1994). Significantly, the introduction of movement can be used to highlight subtle changes which otherwise might be overlooked. However, the programming effort and computer power needed to produce good animation can be overwhelming (Maguire 1985).

Virtual Reality

Brooks (1986, 1988) has reported on the advantages of adopting a virtual reality approach to data presentation. Principally, it has the advantages of 'bringing alive' the domain by providing a means for user interaction with the domain objects. The explicit selection of an interface 'metaphor' helps to define issues and retain consistent decisions (e.g. navigation through a 3D scene may be by walking or flying).

Objects should always move realistically, through scarifying image resolution or reducing model complexity if necessary (as soon as the user terminates their virtual motion, the resolution and image detail return to normal). To enhance illusion, other senses may be used (e.g. sound effects when objects collide). Preece (1994) argues for compelling sensory cues to be created to give the user a strong subjective sense of 'physical presence' and 'direct experience'. These cues may be visual, aural or haptic (concerned with the sense of touch caused by force on the body), or some combination. Immersion systems include peripherals such as helmets, gloves and suits.

Desktop systems use a single, large, colour screen for input and output, a 3D pointing device (such as a 3D mouse) and keyboard. 3D virtual sound makes tasks such as tracking moving objects, navigating and being aware of location easier, quicker and more pleasant to perform. Modelling forces and impenetrable objects, requires the representation of tactile perception (e.g. senses of contact, pressure, pain and temperature) and kinaesthetic cues (e.g. awareness where body parts and limbs are in space, both statically and dynamically). The combination of

both perceptions is the haptic perception (e.g. perception of object solidity, texture, vibration, inertia, weight, elasticity, viscosity *etc*).
The usefulness of virtual reality in BS is self-evident: the domain is inherently 3D, tactile and dynamic. It gives rise to the prospect of a direct model enquiry approach whereby the model itself is used to initiate user requests for information on material properties, occupancy schedules, performance variables, system states and the like.

Alphanumeric Data
Sometimes the only way to display information is in alphanumeric format (e.g. general information about the building, climate *etc*). According to Dix *et al* (1998), textual data should be represented in non-capital letters using Serif font for ease of reading. Tullis (1984) has reported that search times decrease where alphanumeric data is aligned, structured, grouped and spaced.

The use of a calendar (e.g. as used for online flight booking) can facilitate efficient interaction by allowing the user to choose the date and time of an enquiry when operating in 'drill-down' mode.

Comparison of Methods
Maguire (1985) compared different coding methods and a summary of the result is given here. The bracketed data are the maximum number of codes (i.e. different displayed objects) for each method. The higher value is the maximum possible number, the lower value is a recommended maximum for rapid, error-free recognition.

- *Alphanumeric (unlimited)* - Highly versatile. Meaning can be self-evident. Location time may be longer than for graphic coding.
- *Shapes (10-20)* - Effective if the shape matches the object or operation being represented.
- *Colour (4-11)* - Attractive and efficient. Excessive use is confusing. Limited value for the colour blind.
- *Line angle (8-11)* - Good in special cases, e.g. for display of wind direction.
- *Line length (3-4)* – Good but can clutter display if many codes are used.
- *Line width (2-3)* – Good for general use.
- *Line style (5-9)* – Good for general use.
- *Object size (3-5)* – Fair for general use. Can take up considerable space. Location time longer than for shape and colour.
- *Brightness (2-4)* - Can cause fatigue, especially if screen contrast is poor.
- *Blink (2-4)* - Good for attracting attention but should be suppressible thereafter. Annoying if overused. Limited to small fields.
- *Reverse video (no data)* - Effective for making data stand out. If large area is rendered in reverse video, screen flicker is more easily perceived and may become problematic
- *Underlining (no data)* - Useful but can reduce text legibility.
- *Combination of codes (unlimited)* - Can reinforce coding but complex combinations can be confusing.

MULTI-VARIANT PERFORMANCE VIEWS

Within the ESP-r system (Clarke 2001), an Integrated Performance View (IPV) is a standard set of performance metrics designed to represent the multi-variant behaviour of a building. IPVs corresponding to different design options may then be compared to determine in which respects one design option gives rise to performance advantages over another. A typical IPV is shown in Figure 1:

A1 & B1. General information – such as project descriptors, images and contact details.

A2. Maximum capacity – diversified totals for heating, cooling and lighting to represent critical equipment sizes and hence capital costs.

A3. Thermal comfort – temporal distribution of some thermal comfort index to indicate the severity of any departure from an acceptable comfort zone.

A4. Visual comfort – temporal distribution of some visual comfort index to relate visual discomfort to any excess/lack of light or problematic contrasts in the field of view.

B2. Environmental emissions – seasonal primary energy demands converted to equivalent gaseous emissions to define environmental impact.

B3. Daylight availability – distribution of daylight levels to give an indication of the potential for daylight utilisation.

B4. Glare sources – potential glare sources are highlighted and quantified within a synthetic colour picture.

C1-3. Primary energy consumption – patterns of primary energy demand, by fuel type, expressed as cumulative profiles for typical seasons.

C4. Energy performance indicators – these comprise the building's annual energy consumption per unit of floor area for each of the fuel use categories.

These IPV entities were taken as the starting point within the present project, with refinements applied relating to the cognitive and perceptual aspects described earlier.

HYPOTHESIS TESTING TOOL

A prototype display program, I^2PV (Interactive, Integrated Performance View) is under development to support a conjecture and test approach to the display issues previously elaborated.

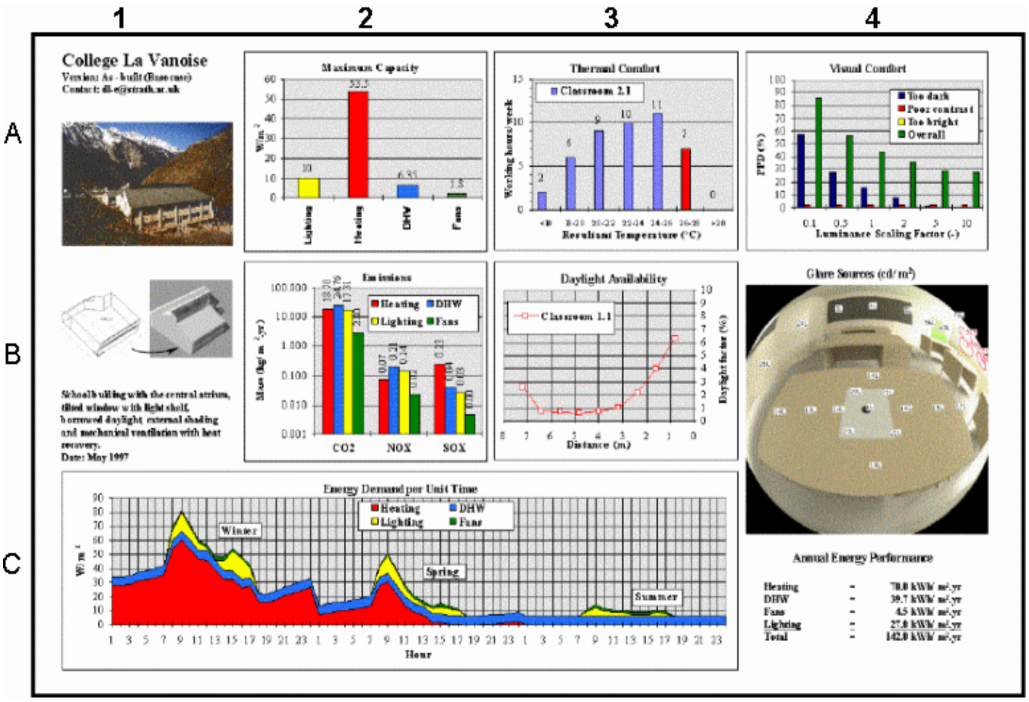

Figure 1: An integrated performance view prior to application of the cognition rules (original in colour).

This tool inter-operates with the ESP-r program although it may be readily interfaced to another BS program. ESP-r (www.esru.strath.ac.uk) is an Open Source system that supports the simulation of the thermal, visual and acoustic performance of buildings, including the energy use and gaseous emissions associated with the environmental control systems and construction materials.

In use, it is intended that the I^{2}PV tool support:

- the presentation of summary data to provide an initial overview of performance;
- ‘drill-down’ data presentations to explore performance in detail; and
- the selection of a communication style that reflects the user's level of expertise.

To ensure platform independence, I^{2}PV is built upon Java; Java 3D and VRML and is thus Web-enabled. Both VRML and Java 3D are designed to allow 3D applets and applications to run on the user’s desktop. VRML defines a standard for 3D for the Internet. It is not an extension to HTML; it is a file format for describing interactive 3D objects and worlds. VRML is capable of representing static and animated 3D and multimedia objects, with hyperlinks to other media such as text, sounds, movies and images.

I^{2}PV supports the display of IPVs comprising content suited to the application context and user type, e.g. designers, energy managers or policy makers when engaged in feasibility studies or actual implementations. Typically, IPV metrics include information on the model, human comfort statistics, energy use data and environmental impact vectors. An IPV allows the user to obtain a balanced insight into building performance. Within the present work, several performance metrics are being added to those listed in the previous section. These relate to acoustic comfort, embedded renewable energy systems, indoor air quality and life cycle assessment.

Figure 2 reproduces the ***A1*** and ***B1*** entities of Figure 1 (corresponding to general information of a design option) with the cognition rules added:

2a. Displays general information in alphanumeric format with the data presented via a scrollable panel.
2b. A calendar identifies the simulated periods, allowing users to change the time focus of the entire IPV. Blinking, coloured days highlight periods with performance metrics above critical values.
2c. Displays a video clip of the project site.
2d. Displays the model and supports interaction to allow the user to change the location focus of the IPV. Both wire-frame and VRML formats are supported.
2e. Gives confirming feedback about the selected zone and time defining the IPV's focus.

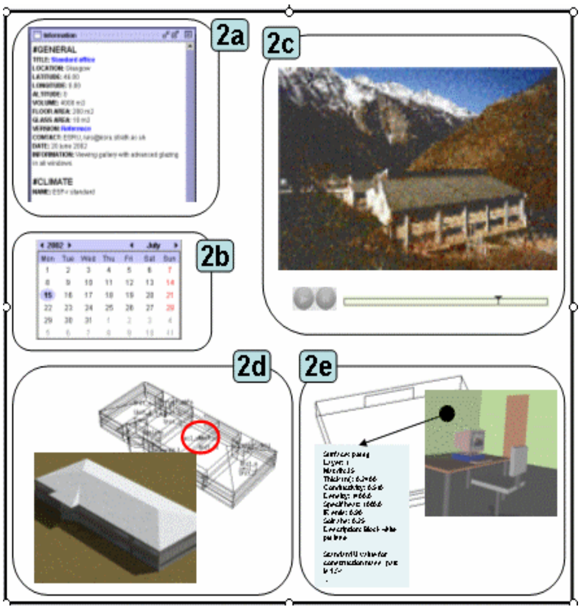

Figure 2: General IPV information with human cognition rules added (original in colour).

Figure 3 reproduces the ***A4*** and ***B4*** entities of Figure 1 (corresponding to visual comfort and glare sources respectively within a zone), again with cognition rules applied.

3a. Allows the user to change focus in relation to model zone and point in time via selection from a menu of alternatives.

3b. Allows the user to define critical visual discomfort levels via a slider.

3c. A 3D view of the selected zone is shown (here a plan) to indicate the possible locations for visual comfort and glare source investigation. The highlighted point is the active one with the available scenes depicted in **3f.** Rotation of the 3D zone view is supported.

3d. Audible warning to indicate that critical value has been exceeded (as set in **3b**).

3e. The eye point location of the selected point is displayed.

3f. Indicates values of the Guth Index for two opposite directions (*1* and 5 shown). Interaction with the diagram gives the visual PPD value for the selected view direction and transfers related data to **3g**.

3g. A slider allows browsing of the image pairs so transferred.

3h. The view numbers are colours green or red to indicate visual comfort or discomfort respectively. The PPD image may then be consulted to determine if a problem is due to too much or too little light or poor contrast.

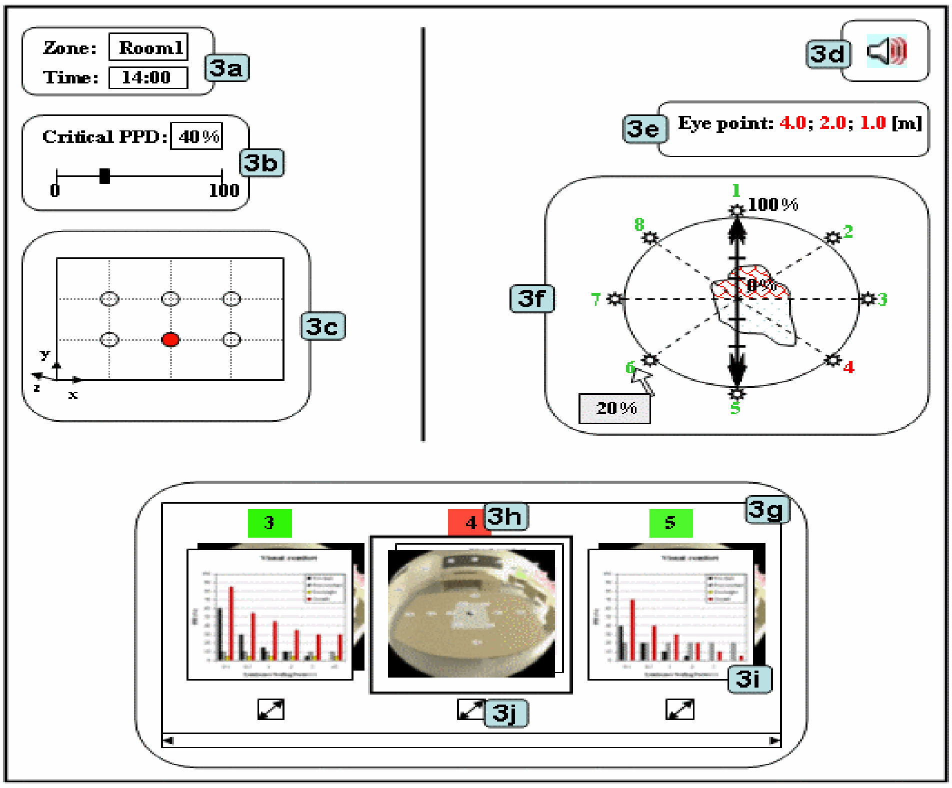

Figure 3: Visual comfort and glare with cognition rules applied (original in colour).

3i. These paired images relate to the glare sources and visual discomfort statistics for the view selected in **3f**.

3j. A toggle to allow switching between the images comprising the **3g** pairs.

A comparison of IPVs supports the identification of trade-offs between design alternatives. Figure 4, for example, depicts a comparison of the energy demand for several design options (i.e. the ***C1-4*** entity of Figure 1). As before, cognition rules are used to assist interpretation.

4a. The zone(s) and period(s) of the enquiry may be defined by the user.

4b. The user can investigate between energy demand (shown here), costs or CO_2 emissions.

4c. Critical peak power and energy demands may be defined by the user.

4d. An audible warning is given when data values exceed these critical values.

4e. An animation controller with play/still buttons and a speed rate setting. This may be used to animate the displayed profiles in order to assist with the scanning and comparison of large data sets.

4f. The profiles corresponding to an arbitrary number design cases may be displayed in this panel, with the slider to the right being used to bring options into the field of view. Profile values may be displayed by positioning the mouse over the point in question. Alternatively, the vertical line dissecting the profiles may be moved to effect temporal comparisons. Instead of displaying just the total energy demand, its break-down can also be displayed (i.e. heating, domestic hot water, fans, lighting *etc*) on the same way.

4g. In animation mode (**4e**), this panel displays the peak variable value(s) (e.g. peak power of temperature) and profile integrated value(s) up to the dissecting line (e.g. energy demand in the case of a power profile).

4h. Displays the corresponding components of the energy demand (i.e. ***C4*** on Figure 1) for the displayed design options.

Two user types are supported at the present time: designers and policy makers. The former is assumed to be interested in the technical message inherent in the data, the latter in the energy consumption trend and the impact of alternative upgrading options. Figures 2-4 correspond to the former user. To support policy makers, the display of Figure 4 has been adapted as shown in Figure 5. As can be seen, entity **5c** employs a different approach to the comparison of design options (i.e. **4f/g/h** on Figure 4) while **5d** displays the penalty of each design relative to the most efficient case (here design 4).

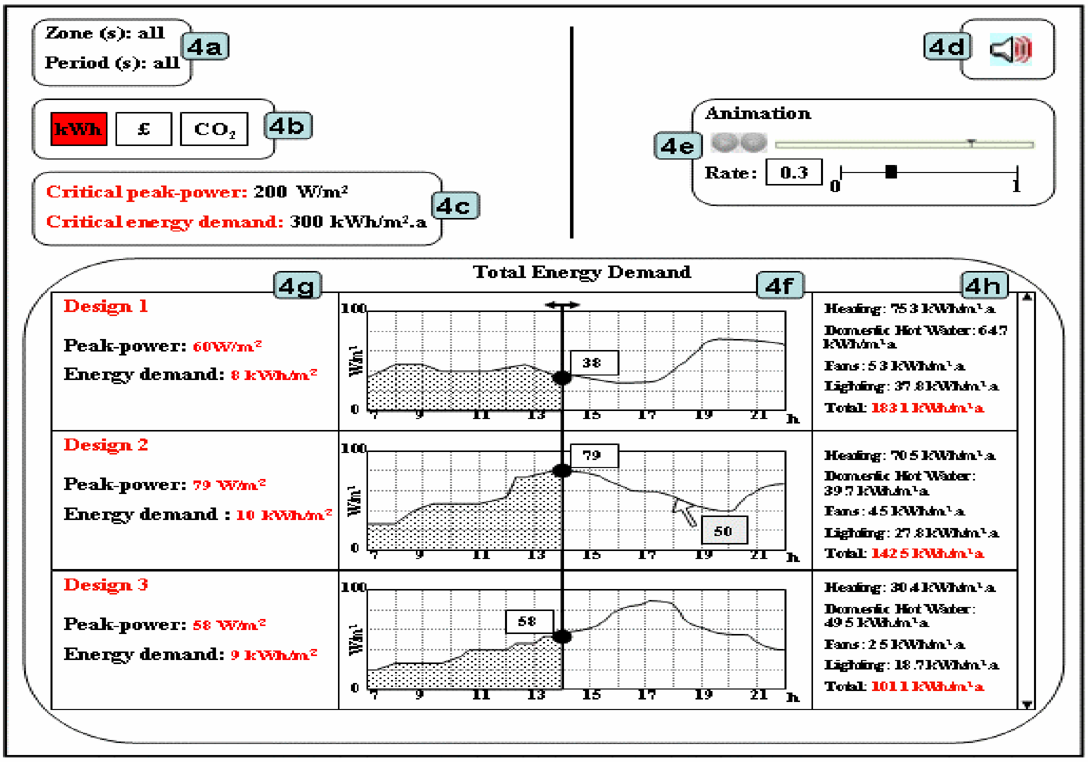

Figure 4: Comparison of design options with human cognition rules applied (original in colour).

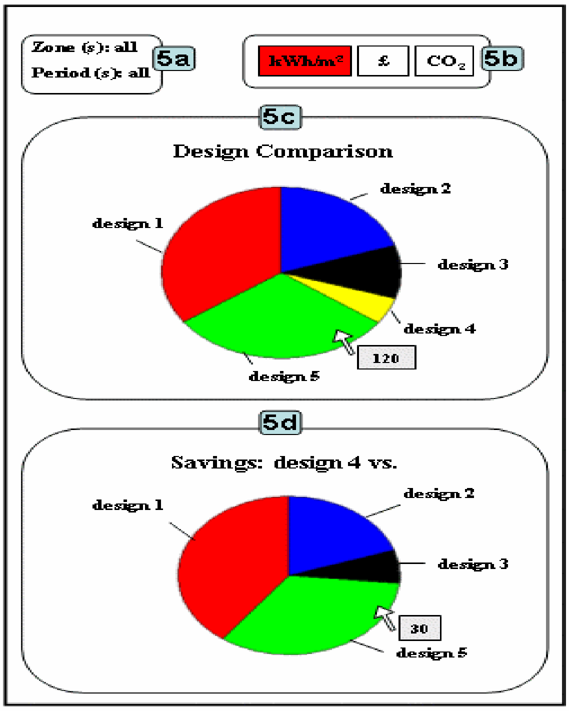

Figure 5: Comparison of design options for policy makers (original in colour).

CONCLUSIONS AND FUTURE WORK

The data emerging from the integrated building simulation process is both vast and complex. Techniques are therefore required to assist users to appreciate and act upon the inherent 'message'.

Based on a literature review, data display conjectures have been formulated and encapsulated within a prototype display tool. The next stage within the project will be to test this tool. This will be done by observing its application in practice and formally recording the outcomes in terms relating to applicability and productivity.

A technique proposed by Wilde *et al* (2002) is also being implemented whereby weightings are assigned to each performance metric to support evaluations in terms of 'does not meet the goal', 'just meets the goal' and 'perfectly meets the goal'. A bubble chart is then plotted to relate costs to benefits, allowing the user to assess performance in terms of only those parameters that exert significant influence, positive or negative, on the building.

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