USING BUILDING SIMULATION TO DRIVE CHANGES IN OCCUPANT BEHAVIOUR: A PILOT STUDY

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ABSTRACT

This paper presents the role of simulation in a large UK research project, eViz, which aims to reduce building energy demand reduction through visualisation. Based on evaluation of various options through simulation, eViz aims to intervene in occupant behaviour and help people to reduce their energy use; the paradigm used is human-in-the-loop analysis, in other words the project anticipates significant interaction with the occupant to arrive at feasible options. The paper presents a pilot study that applies this approach in a domestic property located in the North of England.

INTRODUCTION

It is well-known that however energy efficient a building may be, occupants have a significant impact on its actual energy demand (Branco et al., 2004; Emery & Kippenhan, 2006). This paper reports on a pilot study which is part of a larger project, eViz, that aims to change occupant behaviour in buildings through visualizations, providing intuitive information and supporting decision making while capitalizing on the latest developments in information and communication technology (ICT) such as smart phones, visualization and social media. In general terms eViz aims to make 'the invisible visible' and transform building users into 'smart occupants' who are in control of energy demand. The project will deliver energy reductions that are tied to occupant behaviour and not normally within the scope of building and building services design engineering, building energy management systems, or facilities management procedures.

This paper introduces an initial pilot study, carried out in the context of the wider eViz project, that explores the potential role of simulation when using visualisations to help occupants reduce their energy demand. The pilot study, which focuses on three domestic properties in England, studies the various ways in which normative calculations and transient building simulation can be used to find different courses of action that lead to reduce energy use. These three domestic properties, in which at present building monitoring and building performance simulation are carried out, allow a deep analysis of the capabilities of both approaches to measure and model changes to the occupant behaviour with sufficient signal strength and resolution. This is crucial as a first stage towards developing 'predictive capabilities' that can be used to identify potential changes in occupant behaviour that might reduce building energy use, which then can feed into various forms of energy visualizations that might prompt occupants to indeed change their behaviour. Apart from the typical occupancy representations that are regularly used in building simulation, such as internal heating, lighting and ventilation load schemes that are linked to human presence, the cases also chart a wider range of 'living scenarios', including psychological factors, that might impinge on the feasibility and uptake of suggested interventions in behaviour. The ultimate aim of this work is to create a human-in-the-loop (HITL) thermal building simulation where building performance simulation assesses potential changes in occupant behaviour, triggers the presentation of visual information to those occupants, but occupants then have a free choice in uptake of suggested interventions, upon which the cycle recurs.

This paper first sets the context to the work by introducing the eViz project in more detail. It then presents an initial list of potential energy demand reduction strategies that might help building occupants to reduce energy use. From there, the paper then zooms in on the pilot studies, presenting work on establishing a baseline on occupant behaviour as well as narrowing down available strategies developed from the long list of strategies to those interventions that are deemed feasible in this context. This shortlisting of strategies is then analysed for the optimal way to use computation (both normative calculations and transient simulation) in order to find the most promising strategy. The paper concludes with a discussion of how the computational support will feed into the further eViz work packages, presenting ongoing and future work. The pilot study is fundamental for understanding the prospects of on-the-spot analysis of people in buildings, and provides important insights into the benefits and challenges associated with such approaches.

eViz – ENERGY VISUALISATION FOR CARBON REDUCTION

The eViz project aims to change occupant behaviour in buildings through visualizations, providing intuitive information and supporting decision making while capitalizing on the latest developments in ICT, visualization and social media. In general terms, eViz aims to make 'the invisible visible' and transform building users into 'smart occupants' who are in control of their energy demand. The project intends to deliver energy reductions that are tied to occupant behaviour and not normally within the scope of building and building services design engineering, building energy management systems, or facilities management procedures.

eViz is a strongly integrated project bringing together approaches from social and behavioural science, environmental building, architecture, virtual reality, digital visualisation and computer science. Figure 1 shows the interaction between the different work-packages for the project as a whole.

In relation to building monitoring and performance simulation specifically, the research deliverables sit in work-packages 1 and 2. In essence, WP1 is about 'data on real buildings' and WP2 is about 'data and information on virtual buildings'. Both consequently feed into the following WPs (3-6) to support the visualisations. The visualisations are then intended to lead to interventions, which in turn should register in the measurements in the real buildings as well as able to be studied in the virtual environment.

The building monitoring and performance simulation research which will be undertaken in WPs 1 and 2. At present, eViz is collecting both energy and behavioural data from a series of buildings: three homes with different building types and occupant structures in the South-West and Northeast of England. Monitoring is being set up for a four floor student accommodation building in Plymouth comprised of eight flats of either five or eight en-suite student bedrooms with a shared communal kitchen, and ten domestic properties on a new build housing development in Torquay, UK.

The project will then undertake a series of focussed simulations to study and quantify the impact of a selected series of interventions on the energy demand of these monitored buildings. The simulations will attempt to apply an integrated approach that balances thermal, lighting, indoor air quality and thermal comfort assessment. Initially, the simulation tool IES-VE will be used but other tools such as EnergyPlus, ESP-r, Fluent, Radiance, IDA-ICE will be explored later in the project. It is intended, that the simulations will be validated using the monitoring data. Both measurement and simulation results will be analyzed by means of a search and clustering set-up in either MATLAB or JAVA that can discover patterns and relationships, and ultimately rank the performance of 'behavioural changes'. It will investigate the relationship between the interventions that might be suggested (option space), the energy performance of these options as measured/simulated (outcome space), and our objective functions (energy demand reduction while maintaining health and comfort).

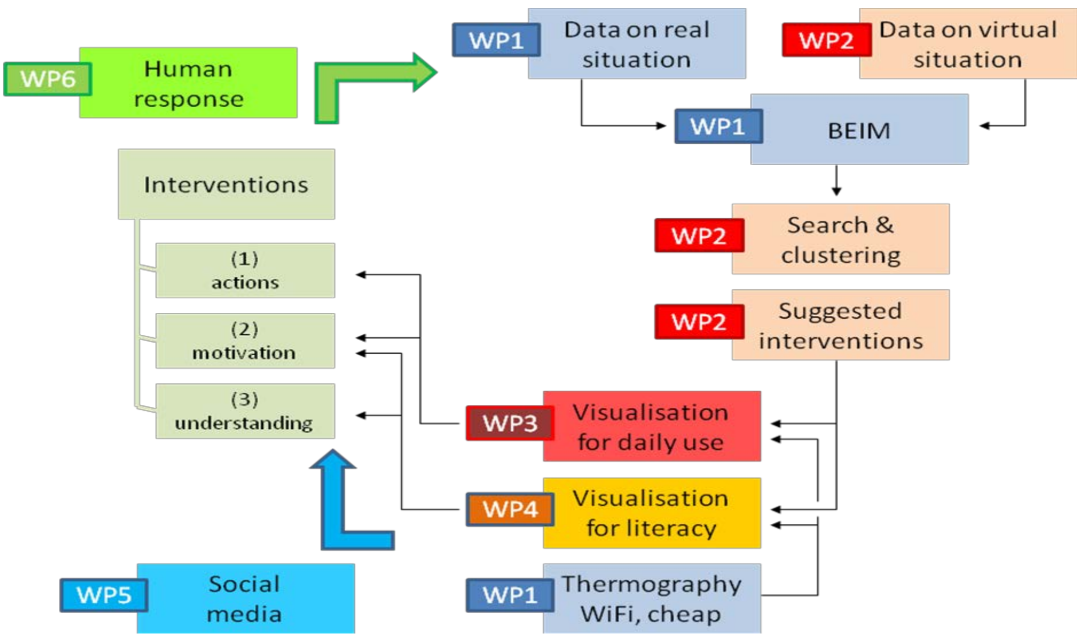

Figure 1 The eViz project approach

PILOT STUDY: BASELINE

In order to explore how the eViz approach will work in real life, an initial pilot study is being undertaken, which aims to go full circle on all work packages. This pilot study focuses on three domestic properties that are currently subject to in-depth monitoring of energy use, thermal behaviour and occupant behaviour.

Hobo U12 data loggers (Tempcon, 2013) have been installed to monitor air temperature and relative humidity every five minutes in a minimum of four different spaces within the homes, including, the living room, main bedroom, kitchen and bathroom. The manufacturers' stated accuracy of the sensors is +/-0.35^{o}C and +/-2.5%RH. The data loggers were placed away from heat sources and not in direct sunlight.

The outdoor environmental conditions (temperature, relative humidity, wind speed, wind direction and rain) are being monitored using a weather station deployed at each home. The manufacturers' stated accuracies for each parameter is: +/-1^{o}C Temp; +/-5% RH; +/-10% wind speed; +/-10% rain.

In addition, a smartenergy system (Alertme, 2013) has been deployed to measure the total electricity use of the dwellings every minute. The data being collected is avaliable in real-time from any Internet enabled device.

Finally, occupant behaviour is being captured using a combination of manual recording (logsheets) and automated methods. The behavioural patterns currently being recorded are home and individual room occupancies, thermostat and radiator TRV settings, and window opening. Hobo UX90-006 movement sensors are being used to automatically collect occupancy information whilst Hobo UX90-001 state loggers combined with window contactors are employed to record window opening and closing.

A small sample of measurements is depicted in Figure 2. This is based on 5 minute interval logging of the indoor air temperature in the living room of one of the case study homes in the Southwest of England. The profile shows the large impact of occupancy; one can discern the daily fluctuations for two weeks, then a stabilization towards 10^{o}C for a week when the occupants were away, then a resumption of the daily pattern. Zooming in on one daily cycle, it can be seen that temperature falls during night time, then a resumption during the day when the heating is on.

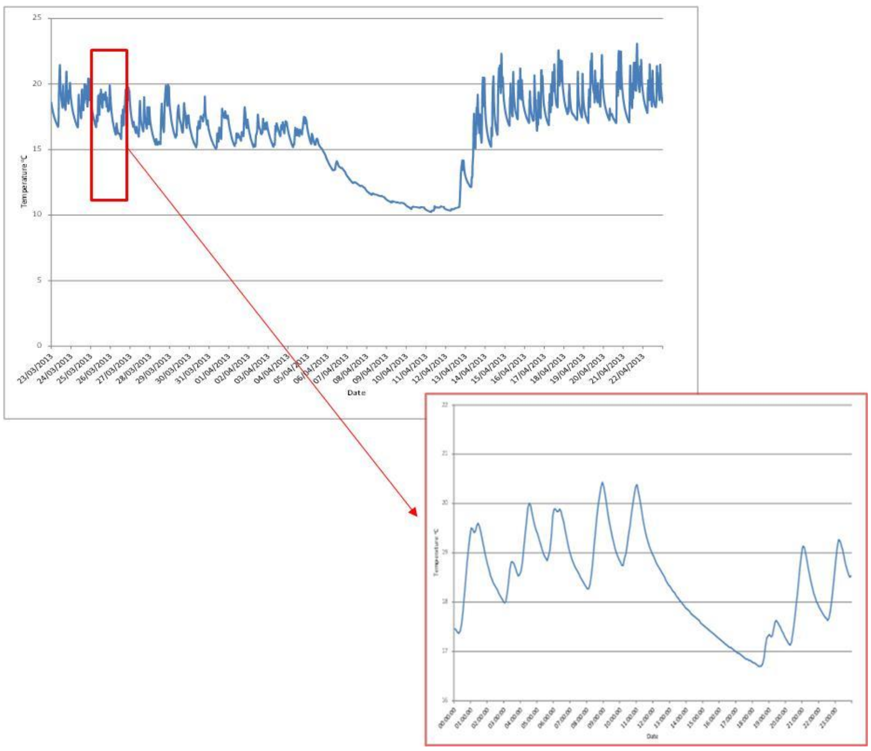

Figure 2 Monitoring data (indoor air temperature) for one case study building, living room. Monthly data 23/3 - 22/4 (top) and single day data 25/3 (bottom)

Work is presently ongoing to replicate these measurement data using simulation in EnergyPlus. A crude initial result is presented in Figure 3. While the simulated overall annual energy use is similar to measurement energy consumption, obviously meeting the actual temperature profile requires a much more extensive calibration of the model. At this point, the behavioural aspect of the eViz project becomes crucial - whereas a basic pattern in the temperature profile will be dependent on weather conditions, HVAC set point values and physical properties of the home, actually matching the measurement results depends on closely logging internal heat loads in the room (occupancy, operation of any equipment that generates heat), ventilation patterns, and overrides on the HVAC system settings. Initial efforts show that the use of simple logging sheets seem to at best give a crude indication, but are insufficient to actually reproduce monitoring data by means of EnergyPlus.

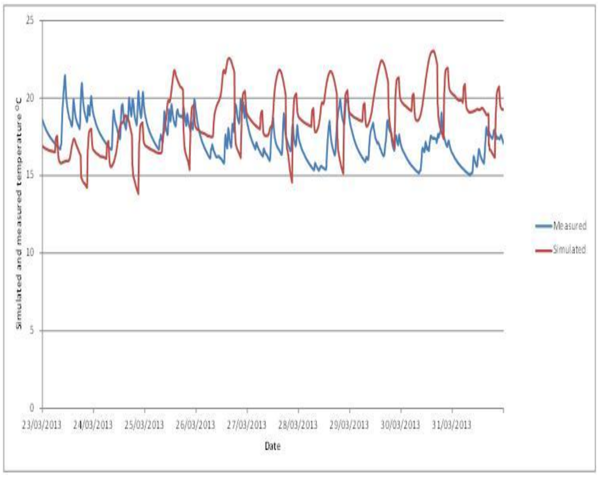

Figure 3: measured versus simulated temperature profile in the living room, 23/3

PILOT STUDY: INTERVENTIONS

One of the other properties is discussed in this paper as an example of how eViz expects to deal with simulation challenges in supporting the overall approach. This property is located in the North of England. The house is an interwar construction from the 1930's; all walls are double brick leafs with a 5mm cavity that has been insulated around 2002. These properties are characterized by higher ceiling heights on the ground floor and large window-to-wall ratios. All original timber frame windows were replaced by double glazed windows of clear glazing. A conservatory was added in 2005 and used a number of high performance materials to conserve energy: the roof is a triple layer polycarbonate, the aluminium frames have interlocking sections and were preassembled offsite to eliminate condensation and infiltration, the timber floor has 100 mm dense EPS under-floor insulation (Styrofoam). The glass is Pilkington double glass casements with K glass on the inner leaf. K-class has a pyrolitically on-line coated low-emissivity glass. It offers substantial improvement on thermal insulation when compared to clear float glass.

The property is characterised by high solar heat gain, which means that as well as retaining heating warmth in a room, it allows high level of solar energy to enter, for warmer and brighter interiors in sunny spells, and reduced heating and lighting costs. All doors are un-insulated including the external door, which are the original doors of the property. The house was renovated as it changed hands and currently the living spaces are open to each other and to the conservatory leading to a rectilinear open space. Floor plans for this property are provided in Figure 4.

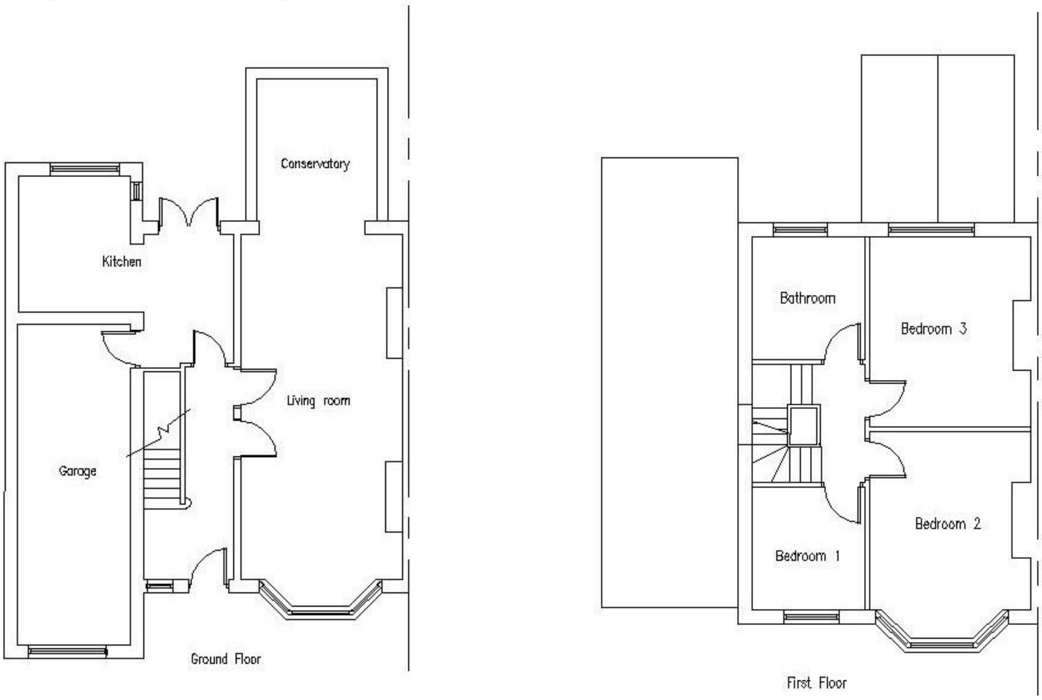

Figure 4 Floor plans of the pilot study property

BEHAVIOURAL INTERVENTIONS

Within this pilot study building, there are many different ways to reduce energy demand. An initial classification of options is presented in Table 1, which discerns four categories. Within Table 1, the columns are defined by whether an energy reduction strategy impacts on the heating or cooling energy, or on energy use by appliances, lighting etc. The rows are defined by whether a strategy is based on changes to behaviour or control, or changes to the building fabric and systems - in other words, hardware change. Note that strategies with respect to the behaviour and control row depend on frequencies and durations, and typically come at no additional cost; strategies that involve changes to building systems and structure typically require substantial financial investments.

Table 1
Classification of energy demand reduction strategies

	Heating/Cooling	Via appliances, lighting etc.
Changes to behaviour or control	Category 1	Category 2
Changes to building systems and structure	Category 3	Category 4

Examples of energy demand reduction strategies in each category are provided in Table 2. Note that Table 2 is indicative only for the many options available to homeowners and occupants. See for instance the ASHRAE handbook for systems and equipment (2012).

Obviously, a staged approach is needed to hone in on specific energy demand reduction strategies that are of interest in the actual context: even for the simplified examples provided in Table 2, and assuming each strategy is either applied or not, one ends up with an extreme search space that consists of $2^7 \times 2^5 \times 2^8 \times 2^4 = 16{,}8 \cdot 10^6$ alternatives - without even considering any parameter variation in each of the alternatives.

While computational power is increasing and the use of meta-models (Eisenhower, 2012) might offer future inroads to handling such large search spaces, eViz follows a pragmatic approach that employs the human-in-the-loop (HITL) paradigm to reduce the search space. Figure 5 shows this option space reduction diagrammatically. On the left hand there is the almost endless option space of strategies that can be employed to reduce energy demand. We apply pre-screening, where the occupant can select those options that are of real interest, as well as account for particular building aspects (some options might not be feasible for a whole range of reasons); this has the advantage that it ensures the later eViz visualisations will come up with alternatives that have a higher likelihood of uptake and will not bother the occupant with endless lists of options that are only remotely of interest or not available to their current living conditions, as unfeasible suggestions might lead to a quick loss of interest in eViz visualizations altogether. The strongly reduced option space then will form the basis of computational exploration, either by normative calculation or by transient simulation. However, since the option space is now strongly reduced it is possible to make the option assessment more intelligent.

Table 2
Examples of energy demand reduction strategies

Category 1
Changing window/door operation behaviour; Changing blind/curtain operation behaviour; Changing thermostat operation behaviour; ... and others.
Category 2
Changing lighting operation behaviour; Changing shower/bathroom usage behaviour; Changing cooking behaviour; ... and others.
Category 3
Adding insulation to walls, floors or lofts; Upgrading to double/triple glazing windows; Installing energy-efficient heating systems; Installing energy-efficient boilers; ... and many others.
Category 4
Installing renewable energy resources (solar panel, heat pump etc.); Installing energy efficient appliances (washing machine, refrigerator etc.); Using energy efficient bulbs; Applying dimmable lighting systems; ... and many others.

Results can be used to rank order options. Other options are to present occupants with the typical time series that result from energy. For instance, rather than blindly comparing energy use of system X with system Y, one can now include the impact of parameter permutation, e.g. subtle changes in operation regime, allowing the inclusion of selected context-specific 'what if' questions in the analysis. Further post-processing is also possible, e.g. calculation of more advanced performance indicators (e.g. expected cost savings per annum, or reduction in carbon emissions). The eViz research team is currently only entering on the visualization; the debate is still ongoing on how to filter and represent simulation results to the occupants. In theory, one could feed forward the simulation results as they are, or postprocess them into vivid imagery that might increase the attention to the outcomes; it is likely that a second filter (user intervention) is needed at this point in the data flow.

As an example, the owner of the pilot study has only a limited interest in some of the renewable energy technology, due to a strong opinion about the aesthetics as well as financial constraints. In terms of reducing the energy demand of the property, therefore the key strategies of interest are relatively straightforward: installation of a door to the conservatory, to control heat loss during cold ambient temperatures, and upgrade of curtains for the same purpose. Options like installation of a PV array or heat pump are not of interest.

The two options, "doors" and "curtains" yield a simple option space but are complex through the many operational regimes possible. For instance, both could be operated at fixed times of day; or based on indoor temperatures, outdoor temperature, the difference between indoor and outdoor temperature, or even on the basis of weather prediction for the next 12 hours. Their operation might also depend on time of year, and external scenarios such as work schedule of the occupants leading to periods of prolonged occupancy and absence.

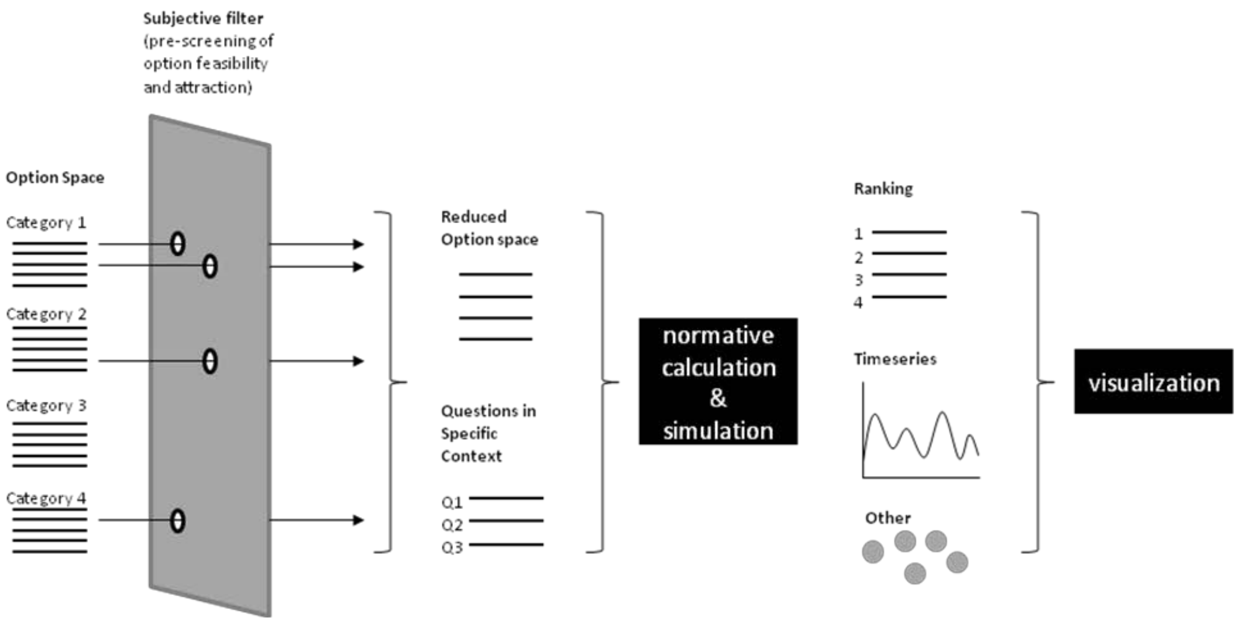

Figure 5: human-in-the-loop option space definition

INTELLIGENT STEERING

As will be obvious from Figure 3, eViz will not blindly opt for simulation approaches for all rankings required by occupants. In many cases, especially where there is a choice to be made between different hardware options, use can be made of normative calculations such as ISO 13790 (ISO, 2008). Use of the normative methods is especially beneficial where changes to the property also need to pass building control, and there thus is a need to use similar calculations such as SAP as enshrined in building legislation. However, in other cases the use of transient thermal simulation is appropriate, for instance to get a handle on the different energy reductions that might stem from installing the door to the conservatory, taking into account different operation regimes.

For the pilot study, the commercial simulation software IES-VE version 6.0.4.11 is used for analysing the energy performance of the pilot study property. IES-VE incorporates a set of integrated analysis tools for investigating different climatic and energy related scenarios (IES, 2012). In the pilot study, the software package is used to simulate the energy performance of the building in terms of the required annual heating plant sensible load. Certain interventions including closing and opening rooms' doors and installing curtains are examined and compared to each other to identify their effect on the annual heating plant sensible load for the house. Figure 6 shows the visual model of the pilot study house established in IES-VE.

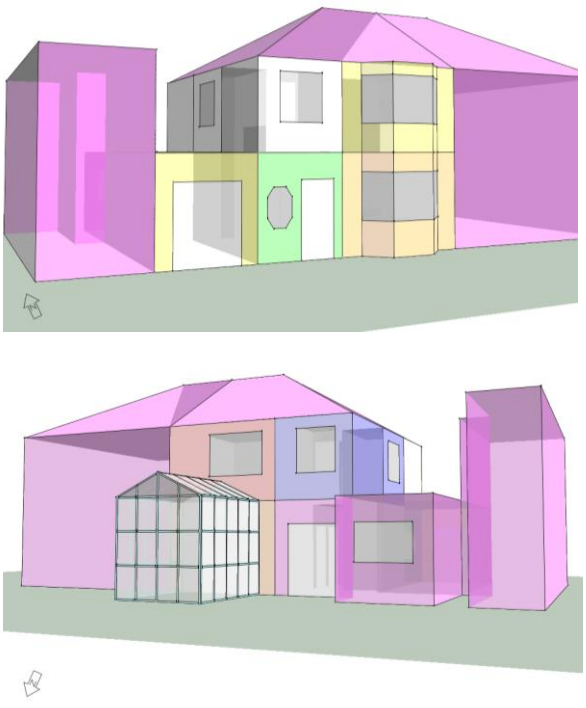

Figure 6: The IES-VE model from front (top) and back (bottom)

Using this model, a range of door and curtain operation scenarios have been investigated. See Table 3.

The orientation of the conservatory is towards the North, this is the worst orientation in terms of direct solar gain but provides much needed and available uniform daylight for the occupants. It should be noted that complex variation profiles for ventilation were used to mimic occupants' hourly and actual engagement with windows in the house over the critical months of winter. All windows are presumed to open 5% of the window area. The bathroom window is opened daily form 9a.m. to 3p.m., bedrooms and living space are opened from 8.30-9a.m. or if indoor temperatures exceed 22C in summer. The conservatory windows are only opened if the summer indoor temperatures exceed 22C.

Table 3
Scenarios studies for Case Study

	Door operation	Curtain operation
Scenario 1 (base case)	Doors always closed	Curtains always open
Scenario 2	Always open (apart from bathroom and garage doors)	Curtains always open
Scenario 3	Closed when room occupied	Curtains always open
Scenario 4	Doors always closed	Bedrooms and living room always closed
Scenario 5	Doors always closed	Curtains on all windows and closed only when occupied
Scenario 6	Doors always closed	Curtains on all windows, open between 08:00-18:00 and closed between 18:00-08:00.

Various occupancy profiles are used to capture the varying nature of occupancy between normal week days and longer mid-term, Christmas, Easter and summer holidays and weekends. Typical reported energy consumption figures for new medium consumption dwellings is predicted at 16,500kWh and for the old typical medium consumption at 20,500KWh (Ofgem, 2011). As the house under study is an old house that has undergone several measures of fabric thermal performance improvements all simulated scenarios are within an acceptable range to the averaged published consumption rates.

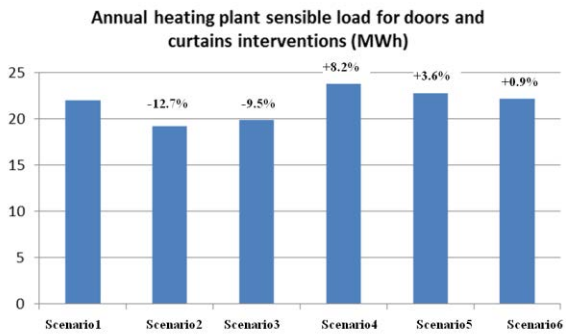

Figure 7: Annual heating load predictions

Results indicate that opening doors between inhibited rooms and maintaining the room air temperatures at 21C is the least energy-consuming scenario. This may be explained by the reduction of the impact of fabric thermal exchanges to the occupied volumes; facilitating a uniform room temperature profile indoors. The simulations then used scenario 2 but conservatory windows where now assumed continuously closed. This was changed as initial simulation showed that the software was unable to calculate a scenario where rooms were required to be maintained at 23C but with windows opened and led to an exaggerated energy demand, but other ventilation profiles for the bedrooms were maintained opened for air quality between 8.30-9a.m. To look at the impact of increasing room set points. It was observed that during the winter period when the house is fully occupied by the family and visiting elderly parents and when outdoor temperatures dip to zero levels over the Christmas period and Easter breaks that a higher set point is used (up to 23C).

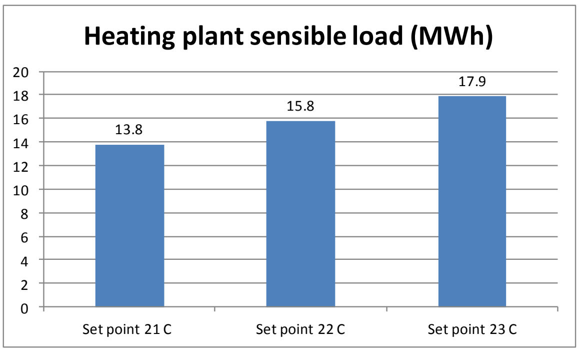

Figure 8: Sensible heating load predictions

This has a relationship with the mean radiant temperature indoors and the perceived level of thermal comfort. As expected this had an impact on increasing the heating sensible loads

ONGOING AND FUTURE WORK

Ongoing work is currently exploring how this type of information is best presented to occupants. Various options are being investigated, including direct display of simulation outcomes as well as more visually attractive displays. In this area, initial focus group studies are being undertaken to investigate lay-people expectations, understanding and requirements. Said work takes place on the interface between building simulation science, psychology, and digital arts.

CONCLUSIONS

This paper discusses the role of simulation in the eViz project, which aims to reduce building energy demand reduction through visualisation. After presenting the overall structure of eViz, the paper focuses on a pilot study to present the detail of how eViz plans to intervene in occupant behaviour and help people to reduce their energy use. The paper points out the complexity of dealing with occupant steering, where a large option space needs to be explored. Human-in-the-loop analysis is used to focus computational efforts (either by simulation or normative calculations) on alternatives that are deemed feasible by occupants. The paper then presents a pilot study that applies this approach in a domestic property located in the North of England. This demonstrates that even for a straightforward example there is a need to explore a whole range of potential behavioural alternatives, leading to significant computational complexity. Ways to represent and visualize simulations in a way that actually encourages occupants to change their behaviour is currently explored in further research.

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