CASE STUDIES OF THE EFFECTIVENESS OF 4D BUILDING PERFORMANCE VISUALISATION

Panagiotis Patlakas[1], Georgios Koronaios[2], Rokia Raslan[3] & Hasim Altan[4]

[1] CEBE, Birmingham City University, UK, panagiotis.patlakas@bcu.ac.uk
[2] Mendick Waring Ltd, London, UK, geo-arch@hotmail.com
[3] UCL IEDE, University College London, UK, r.raslan@ucl.ac.uk
[4] Department of Architectural Engineering, University of Sharjah, Sharjah, UAE, haltan@sharjah.ac.ae

Abstract: *The performance gap between simulation and reality has been identified as a major challenge to achieving sustainability in the Built Environment. While Post-Occupancy Evaluation (POE) surveys are an integral part of better understanding building performance, and thus addressing this issue, the importance of POE remains relatively unacknowledged within the wider Built Environment community. A possible reason that has been highlighted is that POE survey data is not easily understood and utilisable by non-expert stakeholders, including designers. A potential method by which to address this is visualisation, whose benefits in communicating big datasets are well-established. This paper presents two case studies where EnViz, a prototype software application developed for research purposes, was utilised and its effectiveness tested via a range of analysis tasks. Both case studies refer to buildings in central London, and included data collected from POE studies as part of bigger projects. In the first case study, the effectiveness of the application compared to standard tables and graphs was measured via a web survey of 100 participants. In the second case study, a group of 10 participants undertook a range of tasks in order to evaluate how EnViz, and 3D/4D visualisation more generally, allowed them to comprehend POE data and thus influence their decision-making when it comes to applying environmental design fundamentals. The results are discussed and compared with those of previous work that utilised variations of the methods presented here. The paper concludes by presenting the lessons drawn from the five-year period of EnViz, emphasizing the potential of environmental visualisation for decision support in environmental design and engineering for the built environment, and suggests directions for future development.*

Keywords: *Post-occupancy evaluation, 4D Visualisation, performance gap*

1 Introduction

1.1 Sustainability and the performance gap

Sustainability and climate change have arguably been two of the core concerns of the scientific community over the last decades. Within the Built Environment, the issue has moved from a topic of mostly academic interest in the 1960s to a fundamental concern in design practice. The importance of buildings in achieving global sustainability has also now been recognised by the United Nations (Lucon et al, 2014). A wide number of support actions, including educational drives, subsidies, and others, have been offered at a local, state, or international level to support sustainability in buildings in its various guises. Despite the considerable aforementioned interest and engagement, the desired outcomes have as of yet remained partially elusive.

Contemporary environmental design fundamentally follows processes similar to that adopted in other engineering disciplines: a suggested design is modelled digitally, and its environmental performance and impact is then simulated using appropriate software. A key aim of this process is that the simulation model is sufficiently accurate to provide decisive guidance to designers, and thus promote sustainable and climate-sensitive designs over ones that are less so, while remaining within the client's budget.

In the past two decades, technological advances and widespread adoption of computing has resulted in a range of software packages that aspire to move the field of building simulation and evaluation from academia into design practice. However, when designs relying on such software were built and their real-world performance was tested, they were found to significantly under-perform when compared to the predicted (simulated) performance. A decade ago the term "credibility gap" was first used to describe the difference between the expectations at the design stage and the energy use of a building post-occupancy (Bordass, 2004). Today, the phenomenon is considered widespread enough that this disparity, now more commonly referred to as the "performance gap", is largely taken for granted (De Wilde, 2014).

1.2 The Importance of Post-Occupancy Evaluation

Post-Occupancy Evaluation (POE) is an all-encompassing term for surveys whose aim is to systematically monitor and evaluate the actual performance of a completed building or infrastructure work. POE surveys are categorised into two main types: psychological, where the occupants' or users' satisfaction is recorded, or physiological, where 'hard' data is measured and analysed. A major part of POE surveys focuses on environmental issues, measuring properties such as temperature, relative humidity, concentration of CO_2 particles, illuminance levels etc.

The aim of POE analysis is two-fold: firstly, an understanding of the performance of a building can assist owners, facility managers, users, and other building stakeholders in optimising their behaviour to achieve what can be considered 'ideal' environmental performance. Secondly, designers, engineers, and researchers can evaluate actual performance (as opposed to intended performance), and thus have a robust evidence base against which they can benchmark the accuracy of simulation processes and efficacy of designs.

This loop process of design – simulation – construction – monitoring – analysis is common in most fields of engineering design and both its theoretical importance and practical efficiency is largely considered to be routine in such fields. However, while ideal in theory, this process is less easily applicable in environmentally-conscious and climate-sensitive architectural design. While researchers and environmental specialists are generally able to handle with the large amounts of data generated by modern measurement techniques, this is not necessarily the case for other stakeholders. Building owners, facilities managers, senior managers, and architectural designers are just some examples of stakeholders who may be less inclined to believe that monitoring data are easily communicable. This could therefore act as an extra barrier to implementing POE surveys more widely or, even when they are conducted, lessen the impact of their findings (Patlakas & Altan, 2012). Given that POE surveys play a fundamental part in sustainability-oriented research, it is self-evident that they need to be promoted and such barriers addressed when and where possible.

1.3 The EnViz software

EnViz (derived from 'Environmental Visualisation') was a prototype research-oriented software application, developed at Southampton Solent University between 2011 and 2013. Its main aim was to highlight and apply the well-established advantages of 4D visualisation (Ware, 2000) into the field of POE analysis. The completed software provides 4D visualisation of temperature and relative humidity POE data, in a 3D-model context. Multiple models can be handled at the same time, and relevant criteria, with a respective tolerance rate (e.g. ±2 °C), can be introduced within the visualisation. The application also includes the relevant CIBSE guidance for the UK (CIBSE, 2006).

The software has both been utilised in a range of test projects, and in a series of workshops to evaluate its efficacy compared to standard methods of analysis with non-expert users. The results from these studies have been documented extensively in previous work (Patlakas et al, 2014). Generally, the 4D visualisation was found to be a powerful tool for the communication of large volumes of data regarding the environmental conditions of buildings, allowing the understanding of such data more quickly and with greater accuracy than standard graph-based methods. In addition, EnViz users found it easier to compare between spaces and place a specific logger reading in the related building context.

This study aims to demonstrate two new case studies, where EnViz was applied to complement POE studies. These case studies aimed to compare design-stage simulation with POE data using 4D visualisation, measure the effectiveness of 4D visualisation in the decision-making process, and finally gauge the importance of visualisation in evaluating and addressing the performance gap.

2 COMPARING SIMULATION & POE DATA

2.1 Building Performance Simulation Software

Computer-based Building Performance Simulation (BPS) started in the research community in the 1960s and is now an integral part of typical design office practice (Zhou, 2013). A range of BPS software is available today, from specialist packages such as EnergyPlus and IES Virtual Environment, to in-built features in general-purpose packages as Autodesk Revit. Such packages typically offer a range of 2d and 3D visualisation options to communicate the results of the simulation, and it has been suggested that these options improve the effective use of modelling results in sustainable design (Jeong et al, 2013). While commercial simulation software packages are able to invest in provision of attractive visualisation capabilities, less emphasis has been placed on the provision of similar visualisation capabilities for POE data analysis. The first case study, has therefore aimed to address this shortcoming.

2.2 Case Study 1: Central House, University College London

Central House, located in Euston in central London, is a building originally leased and then bought by University College London (UCL). The building was recently refurbished to improve its spatial and environmental performance, however no POE had been previously undertaken to investigate its actual "base case" thermal performance beforehand.

For the purposes of this study, the 4th floor of Central House was monitored, utilising HOBO Onset U12-012 data loggers (Onset, 2015). A total of 20 loggers were internally placed in a range of space types including corridors, toilet and shower rooms, meeting rooms, cellular offices, and open plan offices as shown in Figures 1 and 2 (Sang, 2015). The monitoring took place between the 19th of June 2015 and ended on the 10th of July 2015 (21 days). While this is may not adequate for a comprehensive environmental study of the building (especially given the lack of cold-weather data), it was deemed satisfactory for the purposes of this study.

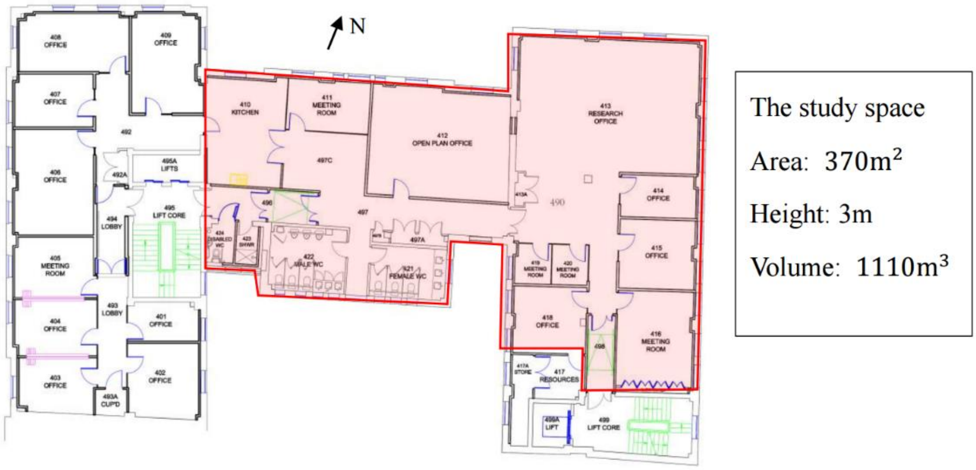

Figure 1: Central House 4th floor overview. The highlight indicates the area of the study (Sang, 2015)

Figure 2: Logger placement. Red dots indicate internal loggers, orange dots loggers near air conditioning units, and blue dots indicate external loggers. (Sang, 2015)

A thermal simulation study of the building was also undertaken for the same period (Sang, 2015) using IES-VS 2014 based on as-designed drawings and some observation-based assumptions by the author. The simulation included the adjacent buildings, as these were deemed to have a significant influence on the indoor environment of the monitored spaces (Figure 3).

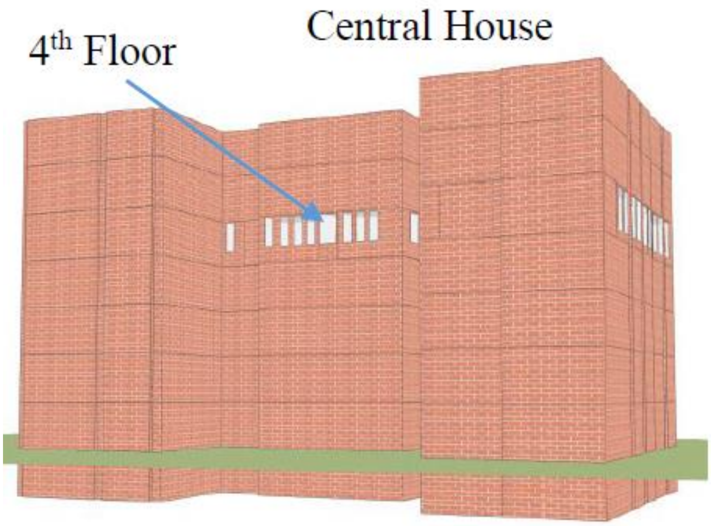

Figure 3: IES model of Central House (Sang, 2015)

The simulation and POE data was input into EnViz to provide a direct comparison of the simulated and the actual performance of the space during the monitored period. Some examples of the resulting visualisations are shown in Figure 4.

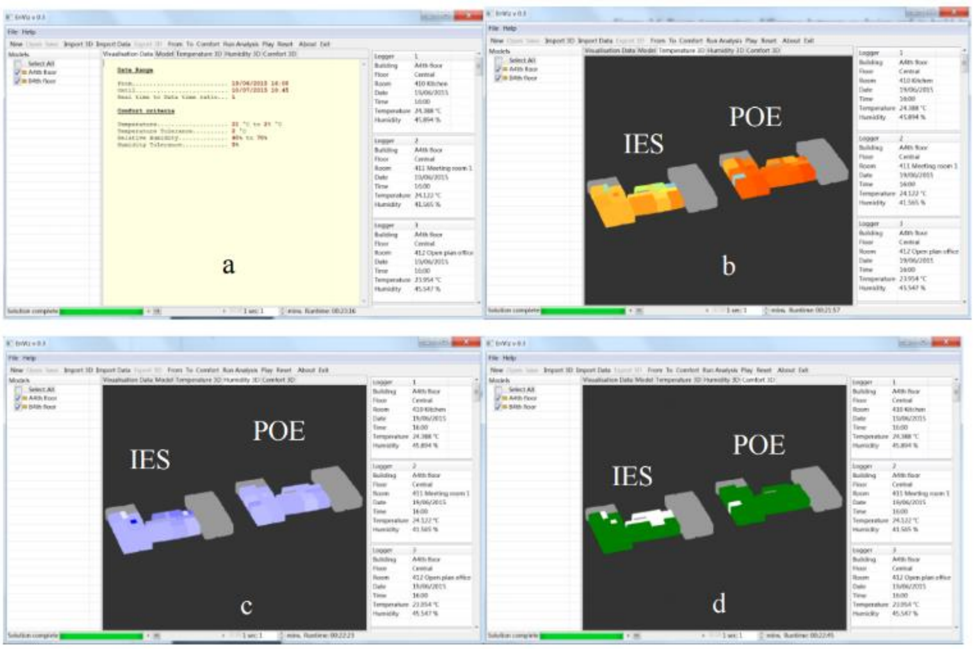

Figure 4: Visualisations of IES and POE data in Enviz (Sang, 2015)
a. EnViz User Inferface; b. Temperature c. Relative Humidity d. Thermal comfort

2.3 Survey of effectiveness of visualisation

Following the completion of the simulation, monitoring, and visualisation process, an online survey was conducted to gauge the effectiveness of the 4D EnViz-based visualisation process in communicating the comparison between the simulation and POE data, as opposed to the current state-of-the-art (typically 2D graphs and tables). Respondents were provided with three representations of the simulation and POE results from a single day. These representations were:
(a) a table
(b) a 2D graph
(c) an EnViz visualisation

The questionnaire consisted of a total of 10 questions, 8 of which concentrated on the direct comparison of the three approaches. These are presented in Table 1.

Table 1: Visualisation comparison questions

Q No.	***Question Text***
Q3	Which (of the figures) do you think shows the detailed temperature most clearly?
Q4	Which (of the figures) do you think shows the temperature change within a month most clearly?
Q5	Which (of the figures) do you think is the best for analysing the temperature difference within a month?
Q6	Which (of the figures)do you think is the most appropriate, in which data is presented to clients/occupants?
Q7	Which (of the figures) do you think is the most interesting?
Q8	Which (of the figures) do you (prefer)?

A total of 100 respondents took part on the online survey. A total of 38% of respondents declared having had been taught about indoor thermal comfort and/or more generally environmental design and engineering. This was in line with expectations, as a number of the building users were either graduate architects or students undertaking an MSc in Environmental Design & Engineering. The answers to Questions 3 to 8 are presented in Figure 5.

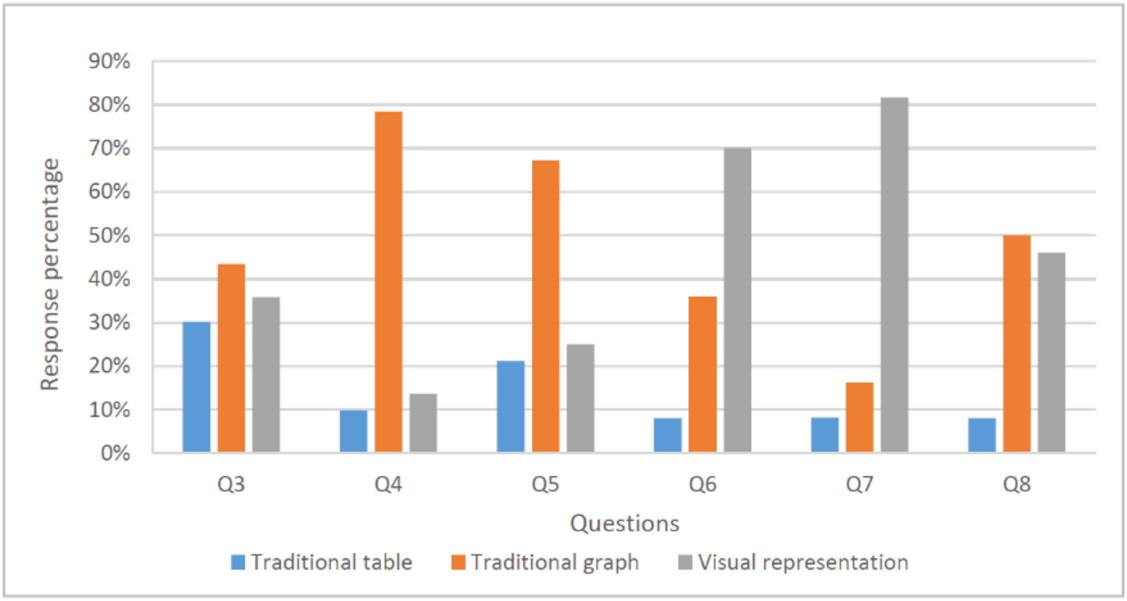

Figure 5: Results to Questions 3 to 8 (Table 1), comparing visualisation options (Sang, 2015)

It is interesting to note that, even though many participants found the graph more useful for comparing temperature changes, they overwhelmingly agreed that the 4D visualisation was the most interesting, and ideal for clients. In addition, the survey only presented data for a single day, i.e. a single day and a single graph. The advantages of 4D visualisation become much more significant when bigger datasets are introduced; previous work has suggested that users find much easier to understand bigger datasets with EnViz compared to data in spreadsheet form (Patlakas et al, 2014). As such it is reasonable to assume that if respondents were presented with bigger datasets, Questions 3 to 5 would have shown different trends.

It should be added that many respondents were critical not of the advantages of 4D visualisation as a principle, but of the specific EnViz implementation. A number of participants commented on the lack of features as compared to commercial-level software. Respondents also mentioned the comparable visualisation with features seen on computer games, which is typically the testing ground of the state-of-the-art in computer graphics.

The detailed results of the building simulation, POE monitoring and analysis, and the questionnaire survey can be found in Sang (2015).

3 MEASURING THE IMPORTANCE OF VISUALISATION IN THE DECISION-MAKING PROCESS

3.1 Case Study 2: 140 Hampstead Rd

The second case study was the (temporary) home of the Bartlett School of Architecture of UCL, Hampstead Rd 140. The building is a former warehouse that was refurbished to meet the needs of an educational studio/ workshop space. The overall rectangular plan configuration includes a lower ground level, a ground level and two additional floors. For the purpose of this study, the examination of all floors was deemed unnecessary. Therefore, the first floor, where the studios of the students of architecture were located, was monitored and analysed (Figure 6).

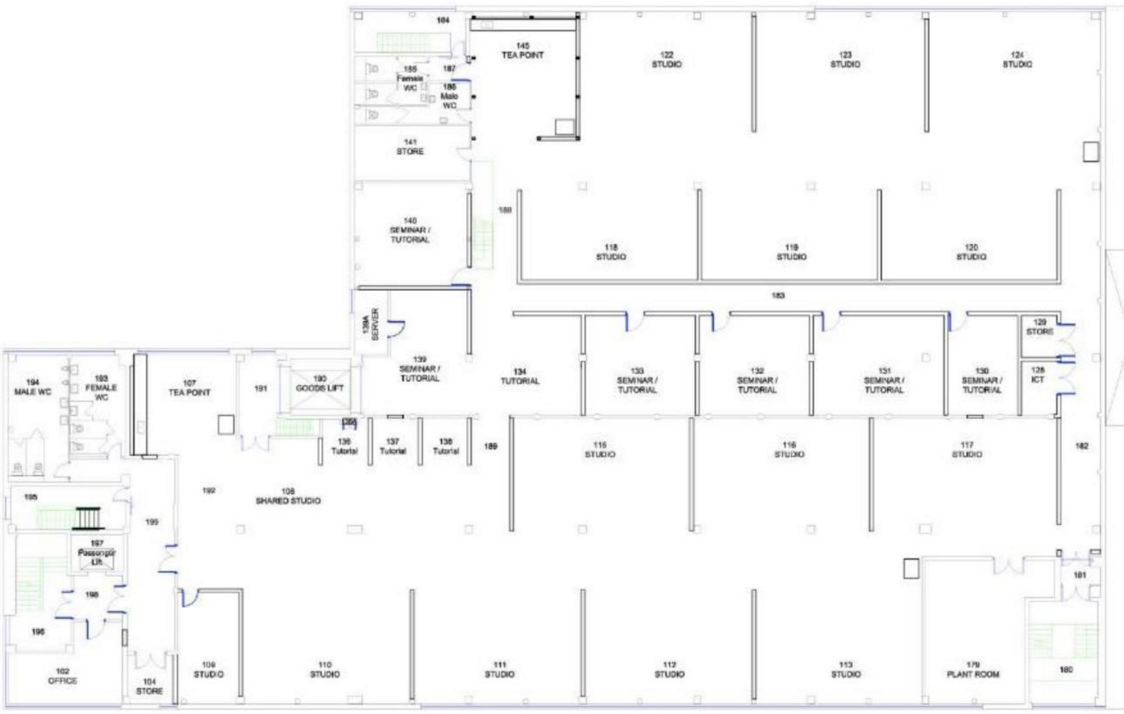

Figure 6: Hampstead Rd 140 1st floor plan

The first floor is divided into two parts (east- and west-facing) which include studios divided by a series of lightweight partitions. These are separated by an row of enclosed seminar rooms and connected by two narrow corridors, which act as a barrier that slightly differentiate thermal conditions between the two zones depending on the time of day. The working and teaching spaces are serviced by a mechanical ventilation system, while the seminar rooms are fully-conditioned through a number of split air-conditioning units.

The observations made on the building were verified via two main categories of selective interviews, based on the time interviewees had spent working on that floor:
Category A: students or teachers that had spent a significant amount of time (over a year)

Category B: summer school students that had only occupied the space for two weeks.
The questions focused on their personal observations on the environmental conditions and occupancy habits/decisions based on their perception of thermal comfort, features of the space they occupied that affected their thermal comfort and environmental performance issues they could point out. Some key observations from the interviews are summarised in Table 2.

Table 2: Key observations from interviews

Topic	*Observations*
Working space preferences	• The majority preferred west-facing studios during the summer • The majority prefers open to enclosed spaces
Thermal comfort perception	• All Category A participants stated the space had very bad thermal performance in both winter (too cold) and summer (too hot) • Half of the Category B participants considered the space to be hot, while the rest was divided between warm and slightly warm • 83.3% stated the space to be slightly dry, while only one individual considered the air to be just right • 100% found the air to be rather still, affecting their perception over their thermal comfort in a negative way • All Category A participants were taking action to improve their thermal comfort(using fans, moving to cooler places)
Layout and architectural elements	• 91.6% believed that the layout did not affect the thermal conditions in a negative way. • The majority was unhappy with the windows as they were not openable. • Lack of shading device enhanced overheating.
Mechanical systems and accessibility	• 33% of Category A participants claimed they had control over the cooling systems • Category B participants were unaware of any existing cooling systems • None of the interviewees believed that the systems installed were adequate for the needs of the entire floor.
Feedback to facilities managers	• Official and unofficial complaints made by full time students and teachers, focusing on lack of adequate cooling and accessibility of controls and windows

Following the interviews, a POE survey was conducted to compare reported perceptions with actual building performance. The monitored period was between the 17th and the 23th of October 2015. Dry-bulb temperature and relative humidity were measured, with a data collection frequency of 10 minutes which resulted in a total of more than 1000 measurements. The data loggers were the same as the ones mentioned in section 2.2 of this paper. The types of spaces monitored are provided in Table 3.

Table 3: Monitored spaces

no.	***Space type***	***Space characteristics***
1	Seminar room	Air Conditioned (cool)
2	Shared Studio	West (heats up later)
3	Studios 12 to 16	West (heats up later)
4	Studio 17	Close to Plant-Room (warm)
5	Studios 19 to 24	East (heats up earlier)
6	Studios 18 and 22	East (heats up earlier)

The POE data were then imported into EnViz, and a range of 3D (static) and 4D (dynamic) visualisations were produced. These were then employed in a series of tasks to measure the effectiveness of the 4D visualisations in decision-making.

3.2 Decision-making Study

For this study, a group of 11 participants with specialist knowledge (prior knowledge of environmental design principles) were chosen, it should be noted that many of the individuals were not familiar with the case study building and none with EnViz. The study consisted of three tasks of increasing complexity, where participants were required to make estimates and take decisions based on EnViz-generated visualisations.

3.2.1 Task 1

For the first task, participants were asked to decide on whether they would take actions to improve the thermal comfort of some spaces, through the evaluation of a specific 3D visualisation (time snapshot) and estimation of temperatures and RH values in each monitored space. A sample screenshot of the visualisation is illustrated in Figure 7.

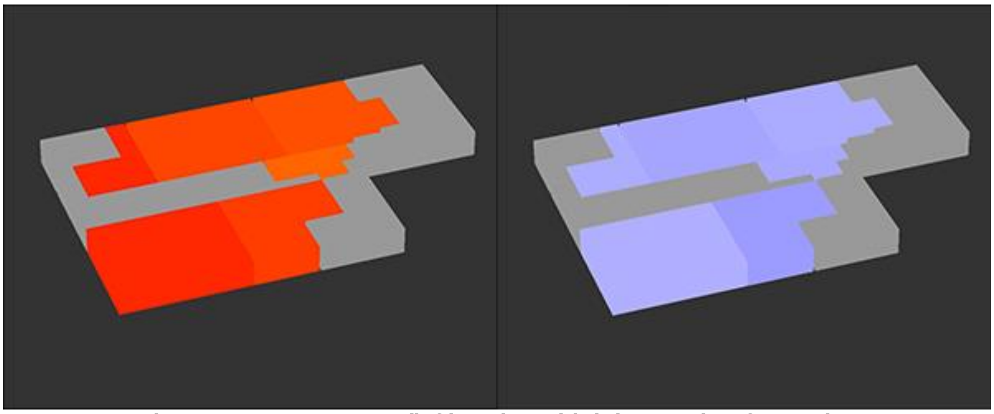

Figure 7: Temperature (left) and RH (right) snapshot for Task 1

For the seminar room all participants stated that they would take no action, while for Studio 17, 10 out of 11 stated that they would relocate, and specifically to the seminar room. For the other spaces, the most frequently stated actions were to readjust clothing and open windows, in order to regulate temperature and increase RH as the humidity was perceived by the participants as significantly lower than it actually was.
It is interesting that participants who were not familiar with the case study showed preference in interacting with the environment by using architectural elements (such as doors and windows) and not mechanical systems. That could be an indication that openable windows should be considered. In addition, it seemed that reading the colour scale of temperature was much more successful and the decisions were instantly made. On the contrary, RH was much harder to identify and comprehend. Thus colour scaling was very important in the comprehension of the visualisation, as a wider RH colour scale

one, was harder to read and identify accurately. The detailed results are provided in Table 4.

Table 4: Decisions to improve thermal comfort in each space

Action	*Seminar room*	*Shared Studio*	*Studios 12 to 16*	*Studio 17*	*Studios 19 to 24*	*Studios 18 and 22*
Relocate	0	1	0	10	4	3
Adjust Clothes	0	4	4	0	2	3
Open Windows	0	5	6	0	4	4

3.2.2 Task 2

The second task attempted to gauge to what extent, the interaction with the software could lead to reasonable assumptions on actual building performance. Participants were presented with a 4D (dynamic) visualisation of the monitored floor for the period between the 24th of July 2015, at 00:00 and the 25th of July 2015, at 15:20. Following this a range of descriptions (such as "Air conditioned", "West facing" etc) were presented in a random order. Participants were then tasked with the identification of the description that corresponded to each floor, by tracking the colour changes in the visualisation.

The success ratio for this task was 100%, which suggests that the tracking feature showing changes in the colour scale in multiple rooms provides a comparative tool that is both comprehensive and intuitive.

3.2.3 Task 3

For the third and final task, participants were asked to take part in a "gamified" decision-making process. The particular rules of the game were developed by the authors and can be found in detail in previous work (Patlakas et al, 2015). In summary, participants were provided with the monitored spaces, some of which failed to fall within the required thermal comfort criteria for some periods of time. They were given a limited budget, appropriately selected so it could not cover all areas, and were then asked to choose which ones they would 'fix' to meet required criteria. A further elaboration was set up, allowing participants to fix either the temperature or the relative humidity aspects in a room. To support their decision-making process, they were provided with EnViz 4D visualisations. Through using the software, they had to track the changes in the colouring of the rooms, estimate their failure rates, and thus prioritize the most important spaces to "fix". Participants performance (i.e. how accurate their decisions were) intended to provide an insight into how accurate conclusions drawn from the 4D visualisation were. The game environment is shown in Figure 8.

Figure 8: Decision-making task 3 environment

The actual failure rates of each space, derived from analysis of the POE data, is presented in Table 4.

Table 4: Failure rates of monitored spaces

Space	*Overall Failure Ratio*	*Failure Ratio (T)*	*Failure Ratio (RH)*
Seminar room	5%	0%	5%
Shared Studio	69%	48%	65%
Studios 12 to 16	62%	59%	45%
Studio 17	81%	81%	37%
Studios 19 to 24	66%	62%	35%
Studios 18 and 22	48%	46%	17%

Table 5 shows the decisions taken by the participants. Specifically, it shows the number of participants that chose to invest in fixing temperature issues (T) and relative humidity (RH) issues for each space, thus indicating they found that space problematic.

Table 5: Participants' decisions

Space	*Fixed T*	*Fixed RH*
Seminar room	0	4
Shared Studio	2	10
Studios 12 to 16	6	4
Studio 17	10	4
Studios 19 to 24	8	4
Studios 18 and 22	6	2

It is clear that through EnViz, the apparent overheating issue in studio 17 and the RH issues in the shared studio were identified and fixed by the participants. The space that was chosen to be fixed the most was Studio 17(10 T fixes and 4 RH fixes), with the shared studio following with 12 fixes, 10 of which was focused on RH. The optimum solution was not achieved in any of the cases. However, it was clear that certain participant decisions derived directly from their use of the software. For example, there was a 100% tendency in fixing the temperature of room 4 and the RH of room 2.
The difference in the distribution between T and RH priorities by the participants, indicated that isolated examination of each of the factors (T and RH), was not very effective providing clarity as to which rooms suffered the most. Namely, it appeared that participants misidentified spaces as failing critically with regard to humidity, when this might not have been the case. However, it is likely that this is due to lack of familiarity with the software and/or the respective colour map and thus could be easily addressed (all participants were EnViz novices).
None of the participants exceeded the budget, but 40% decided not to spend all of it. This suggests that the decision making process was driven initially by apparent failures in the two rooms mentioned above, and the rest by the amount of money left and the possible combinations of fixing the rest without exceeding the budget, and not by the actual needs of the spaces. The full study, together with an analytic documentation of the POE measurements can be found in Koronaios (2015).

4 Conclusions

The work presented here concludes a five-year project in which a prototype software application for the 3D and 4D visualisation of POE data was developed and then tested extensively in order to understand the extent to which visualisation can contribute to communicating the results of POE studies to a wide range of stakeholders, from designers to non-expert building users. The above case studies complement previous work by suggesting additional ways to measure the effectiveness, and their findings largely agree with previous efforts.

In summary, it appears that the conclusions reached in Patlakas et al (2014) hold, namely:

Visualisation can be a powerful tool for the communication of large volumes of data regarding the environmental conditions in buildings.
Visualisation in a three-dimensional model context allows the understanding of building-related data more quickly and with greater accuracy compared to traditional graph-based methods. Time-based (four-dimensional) visualisation provides a better understanding of time-fluctuating data. A volumetric model of a building can be created with a minimal overhead in time and cost. Colour-mapping can be effective in communicating building-related data in a three-dimensional model context.

As in previous work, most of the weaknesses reported by users and survey participants do not focus on the principle of 4D visualisation, but on the inherent, mostly budgetary, limitations between a prototype app developed for research purposes, and commercial, corporate-level software.

Between the start of the EnViz project and today, various initiatives have focused on the visualisation of building data (although using distinctly different approaches). The continuing increase in computational power and ease of software development, together with increased web capacity point towards future developments such as real-time visualisation of building performance and automatic response of buildings to changes in climatic conditions. Simultaneously, the expansion of Building Information Modelling (BIM) means that POE data need to fit into the wider BIM context. In addition, the continuing collection of POE data means bigger and bigger datasets and therefore all the challenges associated with Big Data. Thus, development of suitable digital frameworks is required if the performance gap is to be addressed, and the sustainability agenda furthered.

Acknowledgements

The authors would like to acknowledge the work of Yeyang Sang, aspects of which are presented in Chapter 2 of this paper. The EnViz software development was led by Dr Darren Roberts.

References

BORDASS, B., 2004, 'Energy Performance of Non-Domestic Buildings: Closing the Credibility Gap', In Proceedings of the 2004 Improving Energy Efficiency of Commercial Buildings Conference, Frankfurt, Germany.

CIBSE, 2006, KS06: Comfort, CIBSE, London.

DE WILDE, P., 2014. The gap between predicted and measured energy performance of buildings: A framework for investigation. Automation in Construction, 41, pp.40-49.

JEONG, W.S., KIM, J.B., CLAYTON, M.J., HABERL, J.S., YAN, W., 2013. 'Visualization of Building Energy Performance in Building Information Models'. Proceedings of the Association for Computer Aided Design in Architecture (ACADIA), p.24-27.

KORONAIOS, G., 2015. 'Measuring the effectiveness of 3D visualization in the decision-making process'. Masters dissertation. University College London.

LUCON O., D. ÜRGE-VORSATZ, A. ZAIN AHMED, H. AKBARI, P. BERTOLDI, L.F. CABEZA, N. EYRE, A. GADGIL, L.D.D. HARVEY, Y. JIANG, E. LIPHOTO, S. MIRASGEDIS, S. MURAKAMI, J. PARIKH, C. PYKE, AND M.V. VILARIÑO, 2014: 'Buildings.' In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel.

MENEZES, A.C., CRIPPS, A., BOUCHLAGHEM, D., and BUSWELL, R., 2012, Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap, Applied Energy, 97, pp. 355-364.

ONSET, 2015. HOBO Temperature/Relative Humidity/Light/External Data Logger - U12-012. [Online] Available from: http://www.onsetcomp.com/products/dataloggers/u12-012. [Accessed: 27th July 2015].

PATLAKAS, P. and ALTAN, H., 2012. 'Visualizing Post-Occupancy Evaluation Data: Rationale, methodology and potential of EnViz, a visualization software prototype'. Digital Physicality - Proceedings of the 30th eCAADe Conference - Volume 1, Czech Technical University in Prague, Faculty of Architecture (Czech Republic) 12-14 September 2012, pp. 647-653.

PATLAKAS, P., SANTACRUZ, H.B. and ALTAN, H., 2014. 'Visualising the environmental conditions of buildings'. Proceedings of the Institution of Civil Engineers, 167(5), p.56.

PATLAKAS, P., MANIADIS, Z. and RASLAN, R., 2015. 'Using gamification to enhance understanding of building performance'. ZEMCH 2015 International Conference Proceedings. Lecce, Italy, 22-24 September 2015, pp. 669-683.

SANG, Y. 2015. 2015. 'Comparison of design-stage simulation with POE data, and the importance of visualization in evaluating the performance gap.' Masters dissertation. University College London.

WARE C, 2000. Information Visualisation: Perception for Design. Morgan Kaufmann, San Francisco, CA, USA.

ZHOU, X., Hong, T.Z., Yan, D., 2013. Comparison of Building Energy Modeling Programs: HVAC Systems. [Online] Available from: https://simulationresearch.lbl.gov/sites/all/files/lbnl-6432e_0.pdf. [Accessed: 16th June 2015].