A 'BIG DATA' APPROACH TO THE APPLICATION OF BUILDING PERFORMANCE SIMULATION TO IMPROVE THE OPERATIONAL PERFORMANCE OF LARGE ESTATES

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ABSTRACT

This paper derives from the 'Hit2Gap' project, funded under the European Union's Horizon 2020 R&D programme (Hit2Gap 2015). The aim of the project is to reduce the gap between design intent and the operational performance of large building estates. To this end, a data exchange platform is being prototyped and tested, able to collect and store data from disparate sources and deliver subsets of these data to a range of applications (services) and end users. The ultimate aim is to identify physical interventions that could alleviate operational problems and so reduce the performance gap. This paper deals with the application of building performance simulation (BPS) within the context of data exchange platform and specifically, the delivery of an input model, its automated calibration and use in areas such as HVAC system fault detection and diagnosis, upgrade options appraisal, indoor environment quality improvement, demand reduction, renewable energy systems integration, control system refinement, and regulatory compliance. The paper summarises the Hit2Gap architecture, the procedure for the automatic calibration of BPS models and automated performance assessments.

INTRODUCTION

Design practitioners apply building performance simulation routinely at the design stage as a means to appraise options in terms of their impact on energy use and environmental conditions. Given the uncertainties associated with model parameters, it is unsurprising that predictions are often substantially different from corresponding observations made at the operational stage (de Wilde 2014, Gupta & Gregg 2016, Herrando *et al.* 2016, Lawrence and Keime 2016, Niu *et al.* 2016, Zhao *et al.* 2017). This so-called performance gap is being addressed by improving the fidelity of the design stage model through explicit consideration of occupant behaviour, adding more detail in the representation of microclimate, and/or incorporating consideration of principal parameter uncertainty. The gap may also be addressed at the operational stage by updating and recalibrating the design stage model using monitored data before applying this model to investigate operational problems. The latter approach is one of the aims of the Hit2Gap project.

At the core of the Hit2Gap approach is a cloud-based data platform that provides an open solution to the integration of third party services that address energy use and related issues. These services could cover a spectrum of possibilities, from the extraction of performance improvement advice from monitored conditions, through HVAC fault detection/diagnosis, to model predictive control and options for change appraisal – all aimed at improving operational performance and recovering the design intent. By simplifying the procedure for new service connection, the platform aims to foster initiatives by small and medium enterprise companies, who face major challenges to penetrate a market dominated by large providers of building energy management systems.

Figure 1 depicts the elements of the Hit2Gap platform and the services that may be invoked on the basis of data 'mash-ups' delivered on request. The platform comprises three distinct levels:

- field level, encapsulating sensors and systems for data acquisition, with support for a variety of data acquisition protocols;
- core level, handling data exchange between modules and storing data from measurements and services; and
- management level, comprising services relevant to building operation improvement.

The aspect considered in this paper is the connection of BPS tools, specifically the delivery of their required input model, their calibration to align them with observed performance, and automated simulation to identify remedial actions. Simulation services are implemented as Web clients hosted by the tool provider. For the tool provider, the platform should provide the means to update services without the need for individual user interaction. For facilities managers and other users, the platform should provide the means to access powerful analytic capability with no need to download specific tools and master their idiosyncratic control syntax.

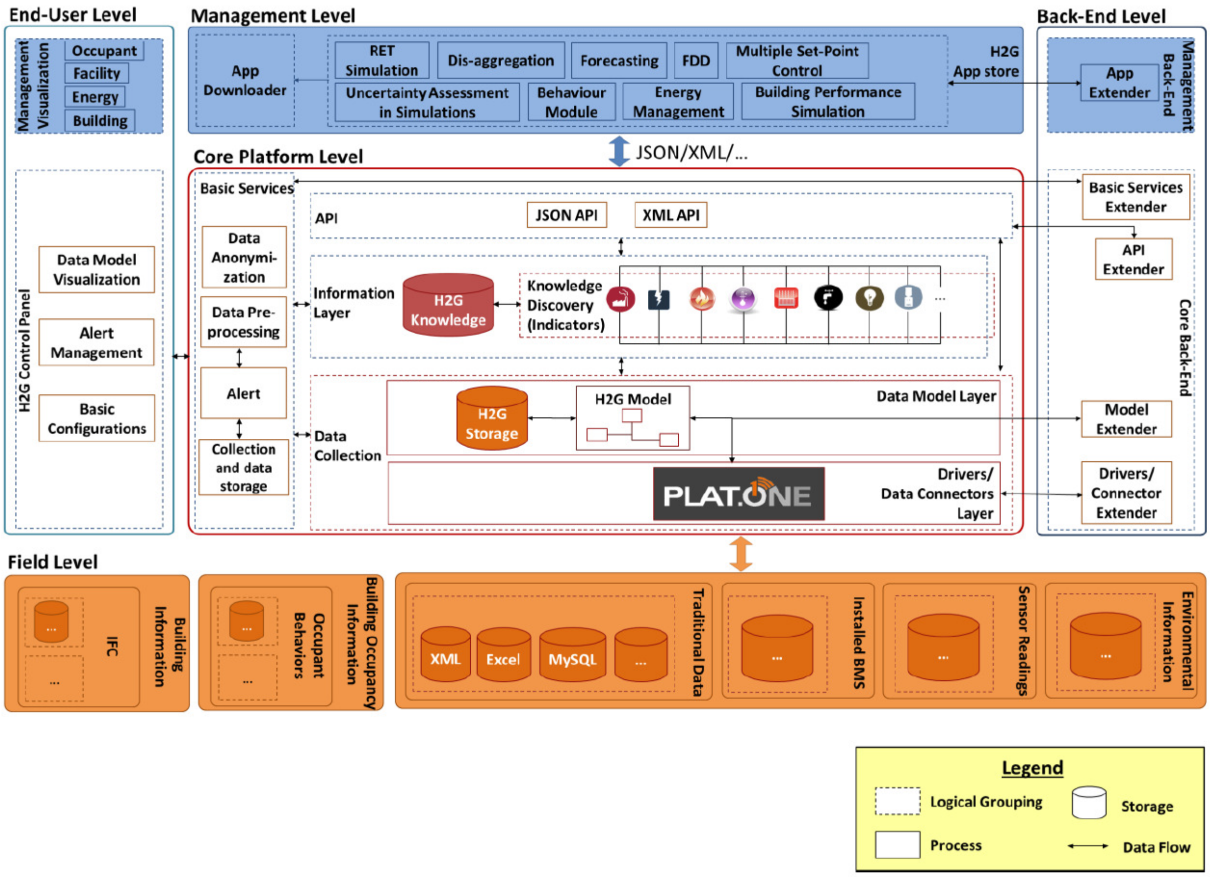

Figure 1: Elements of the Hit2Gap platform (Hit2Gap 2015).

The approach should eliminate the existence of conflicting tool versions, facilitate rapid service updating, and support the harmonisation of service application through the adoption of agreed performance criteria.

The delivery of a BPS service is a three-step process:

- acquisition, comprising the provision of the required input model of the building via the platform;
- calibration, resulting in necessary modifications to the model's principal input parameters to align predictions with actual operation; and
- performance assessment, comprising the invocation of predefined, scripted procedures as a function of detected facility management issues.

At present, the platform offers several representative BPS tools including ESP-r, EnergyPlus, SBEM and new tools relating to the identification of reasons for the performance gap (Gap Reasoner, by the Fraunhofer Institute), HVAC fault detection (by the NUI Galway), renewable energy systems appraisal (RET, by CyRIC), and the superimposition of performance assessment outcomes on IFC-based building geometry display (by ZUTEC). The following sections describe the above steps in more detail.

ACQUIRING THE INPUT MODEL

When a user requests a cloud-based service (e.g. BPS tool), the corresponding tool's input model is retrieved from the platform. In some cases this model will have originated from the design stage and be immediately usable by the tool. In other cases, parts of the required input model may be available, but for be compatible with another tool – for example, building geometry in the case of a CAD tool. By adopting the Industry Foundation Class (IFC) standard (ISO 2013) for building model storage, the intention is to support data reuse within the platform, with supplementary data provided in the tool's native format in the short term. The expectation is that this requirement will diminish as the IFC standard evolves to cover all BPS technical and performance domains, and as a growing number of tools make use of this extended capability.

Within the Hit2Gap project, models have been established for four pilot buildings to demonstrate the procedure for model data sharing and multi-service invocation. These comprise the nanoGUNE office/ laboratory complex in San Sebastian, Spain; the headquarters of Bouygues Construction in Saint

Quentin en Yvelines, France; the city municipality building in Warsaw, Poland; and a teaching/ laboratory building at the University of Galway, Ireland.

AUTOMATED CALIBRATION

A new platform service, named *Calibro* (Monari 2016), has been developed to provide the capability to automatically calibrate any connected BPS tool. The input required comprises data input-output pairs for multiple simulation cases, which capture input parameter and output perturbation. While these input-output parameter pairs will typically depend on the intended application of the BPS tool, they have no particular meaning within Calibro. The calibration method also requires measured values of the output parameters and time-matched weather conditions. Using these data, Calibro constructs an emulation of the connected tool and uses this to determine the input parameter values that will cause the tool to best reproduce the measured performance. The approach, as, utilises four statistical techniques:

- principal components analysis (Hotelling 1936) to reduce the dimensionality of the input data sets;
- sensitivity analysis (Morris 1991) to select the parameters for inclusion in the emulator;
- optimisation based on Gaussian Process (Snelson 2007) to train the emulator; and
- the Markov Chain Monte Carlo method (Gelfand *et al*. 1992) to infer the parameter values and related uncertainties.

The best-fit input parameter values are then returned to the platform to be incorporated in the activated BPS tool's input model. Further, the differences between design stage and final stage parameter values are delivered to the platform as a contribution to an understanding of the causes of the performance gap. The key point to note is that Calibro is tool agnostic and is automated in its application.

Consider the following application of Calibro to two tools intended for significantly different purposes – ESP-r for multi-domain performance simulation (Clarke 2001, Strachan *et al*. 2008) and SBEM for regulations compliance checking (Hitchin 2010) – when each is applied to a specific pilot building.

In the case of ESP-r, a portion of the triple accredited headquarter office complex of Bouygues Construction located near Versailles, France (Wilding 2013) is modelled. BuildAx multi-sensors (Clarke and Hand 2015), as depicted in Figure 2, were deployed in the south triangle building to collected indoor environmental conditions data and weather data acquired from local sources.

In the SBEM application case, the model relates to the Warsaw municipality office complex with energy use data obtained from utility bills.

The inputs required by Calibro were generated by invoking ESP-r's Monte Carlo sensitivity assessment feature (Macdonald and Clarke 2007) and by scripting multiple applications of SBEM with parameter increments applied, respectively. Figure 3 shows typical before and after outcomes in each case.

Figure 2. Deployment of BuildAX multi-sensors in the Bouygues building.

The final goodness-of-fit achieved in both cases is satisfactory, despite the radically different nature of the tools and the temporal scope of the performance data employed in the calibration exercise. Both tools may now be considered suitable for application in the operational context.

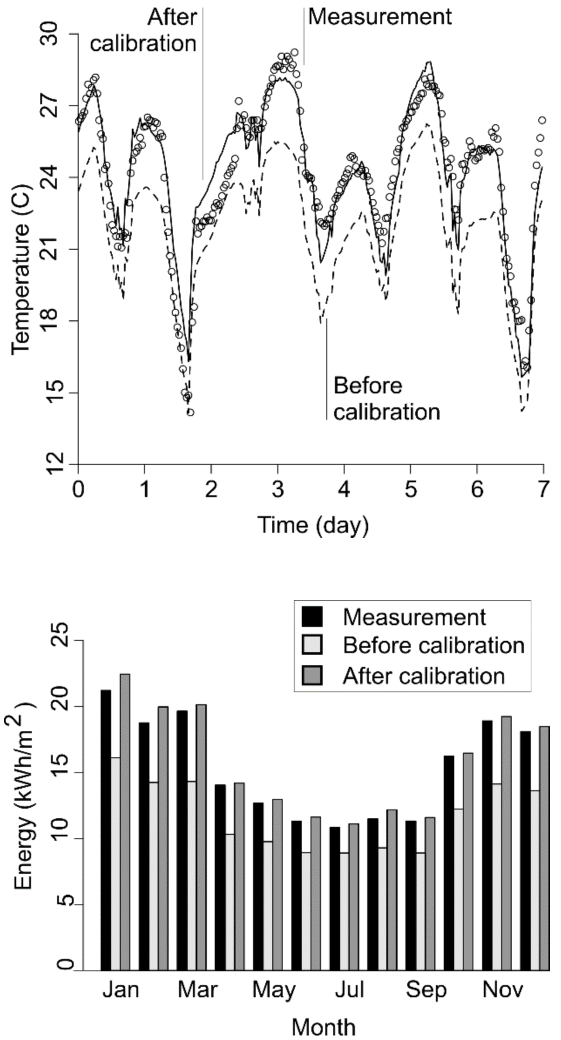

Figure 3: Comparison of ESP (upper) and SBEM (lower) predictions before and after calibration.

Some lessons emerging from the automated calibrations undertaken to date include the following.

Note to reviewer: this material will be quantitatively refined in the final version of the paper based on research outcomes presently being analysed.

While the calibration process benefits from large sets of model input-output pairs, the most time consuming part of the procedure is often the generation of these pairs, especially where the tool does not automate this process. As a rule, it is advisable to work with sets of input-output pairs of size 10 times the number of model parameters being included in the calibration.

Computational time is also dependent on the intrinsic property of the tool being calibrated and especially on the number of calibration parameters and their identifiability. Models dominated by a few principal parameters are easier to calibrate because of faster convergence of the underpinning optimisation and Markov Chain Monte Carlo algorithm. In the presence of strong interactions between calibration parameters, the algorithm may take a significant time to converge.

Modellers should be cautious at first with respect to the degree of complexity of the model used for calibration. A staged approach is advised: the end-user can add more degrees of freedom after analysing the initial calibration results and the residuals between calibrated model outputs and measurements. It should be noted that automatic calibration will not necessarily yield a model that fits the given observations, but calibration results can be used to identify model deficiencies and target improvements, for example by examining modelling assumptions and identifying suitable upgrades. Calibro also provides a means for the comparison of models at different levels of complexity aiming to predict the same phenomena, thus supporting the identification of an appropriate complexity level. In these respects, automatic calibration can be an effective analytical and diagnostic tool for building energy models.

PERFORMANCE ASSESSMENT

Three principal capabilities are required if a BPS tool is to provide automated, cloud-based performance assessment. First, the tool's input model must be capable of manipulation with no need for user interaction. Second, the tool must be capable of automation in relation to simulation process control and results analysis. Last, the tool and its outputs must be able to cooperate with other applications in an automated manner.

Consider an example based on the scripted operation of ESP-r in which the sub-modules of the tool are driven by cooperating, parameterised scripts corresponding to some standard performance assessment. Because ESP-r has its origins in Unix, its sub-modules (for model manipulation, simulation and results analysis *etc.*) and outputs can be freely shared with a vast array of general purpose tools for pattern matching, model editing, image/text manipulation and report generation, etc. These can be incorporated throughout performance assessment scripts as required. The important point is that the procedure is able to process problems of arbitrary complexity while not requiring user interaction.

The approach involves the use of the Unix Bourne Shell (Bourne 1982) as a pseudo expert system shell. Shell scripts are established to coordinate the operation of ESP-r and other programs against the procedures and rules of a particular performance assessment. All such rules are parameterised so that they may be replaced depending on the context of a particular assessment. The computational path to be followed at any stage in the script will depend on the performance data to emerge at previous stages and on the embodied rules. Each shell script can be viewed as a design assistant: the performance assessment path and program operation knowledge is known to the assistant; the user is free to focus their attention on the outcome and its relationship to decision making.

There are many possible performance assessment targets relating to buildings in use and the Hit2Gap project is demonstrating some significant examples: HVAC fault detection and diagnosis, control system optimisation, indoor environment problem alleviation and upgrade options appraisal. Four aspects of indoor environmental quality are being addressed which make use of on ESP-r application scripting. These are as follows.

Thermal comfort

This assesses the quality of the indoor environment in terms of the temporal and spatial distribution of air and mean radiant temperature, relative humidity and local draught. This requires the use of ESP-r's embedded CFD and moisture flow algorithms.

Visual comfort

This assesses the risk of glare under typical seasonal conditions for standard viewing directions relative to external facades. This requires the use of ESP-r's sky radiance model and run-time cooperation with Radiance.

Indoor air quality

This assesses indoor air quality in terms of the temporal and spatial variation of mean age of air and CO_2 levels in principal spaces. This requires the use of ESP-r's CFD and network flow models with CO_2 source injections superimposed.

Overheating avoidance

This assesses the benefits of night ventilation for the avoidance of overheating. This requires the use of detailed systems modelling in the case of mechanical ventilation, and airflow simulation using a network model in the case of natural ventilation.

Consider the thermal comfort expert script shown if Figure 4. Its purpose is to undertake a performance assessment with the following objectives.

- To determine an appropriate simulation boundary condition by selecting a weather collection matched to the building's geographical location.
- To initiate and control an ESP-r simulation over periods determined as a function of relevant outdoor temperature severity criteria.
- To seek out building zones deemed uncomfortable according to activity-specific thermal comfort criteria.
- To recover and present statistics on detected levels of discomfort.
- To determine the cause of discomfort problems.
- To quantify parameter sensitivity as a means to rank order options for design intervention.
- To provide a report on comfort performance, including problem causes and potential cures.

The assessment comprises seven interrelating sub-scripts. The first runs the climate analysis module to determine the weather boundary condition then runs the simulator. The second recovers the state variables that quantify comfort and groups zones according to whether or not they violate the function-related comfort criteria. Summary statistics on the worst performing zones are then gathered. The third script investigates the cause of any discomfort, while the fourth commissions a sensitivity analysis. The fourth and fifth scripts provide the search instructions to the *awk* pattern matching tool to direct the search for the discomfort location and cause respectively. The last script gathers all relevant outputs and prepares the outcome report.

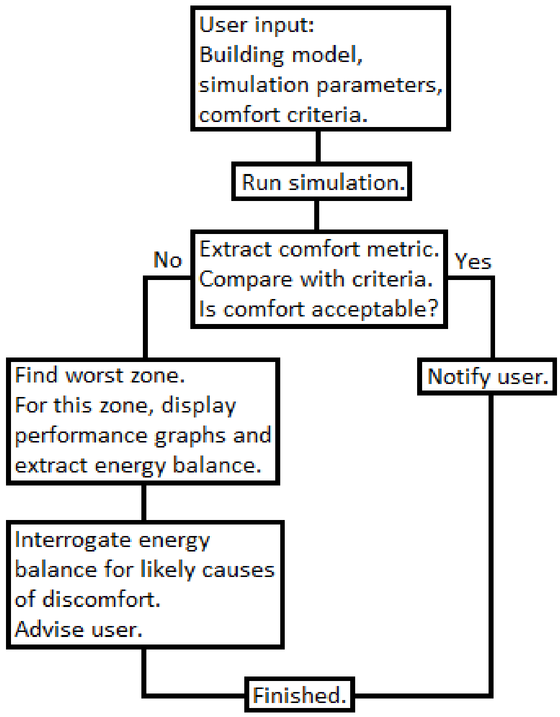

Figure 4: Flow chart of comfort expert script.

To impart a flavour of the process, consider the following script fragments.

```
# start fragment1
  bps  -mode script -file $1 -p  ${period}
  <<~
  ${drivers}
  ~
# end fragment1


# start fragment 2
  OHC='awk -f $eb_pattern $bps_result'
# end fragment2
```

The first fragment instructs the simulation module to operate in script mode, to process an input model as passed from the platform (given as the first argument on the script invocation line, $1), to focus on a given period (${period}), to follow a defined simulation path (${drivers}) and to pass back control to the script when the ~ is encountered. All ESP-r modules are 'driven' in this way, with the selection of ${drivers} depending on the assessment purpose.

The second fragment uses the *awk* pattern matching tool to rank order the energy flows contributing to any detected discomfort. It does this by telling *awk* to apply the search directives of file $eb_pattern to the results database $bps_result' and place the result in parameter OHC, which is then available as input to other script procedures.

Of course, the actual scripts are non-trivial and will require updating in response to any changes in ESP-r's control syntax. However, at the end of the procedure all results are collated and incorporated in a standard report for delivery as required. This report is constructed using *troff* document processing (Ossanna 1976) because of its programmability and ability to provide high quality outputs.

Such procedures are ideal for implementation on cloud-based computing platforms, with user requests and results delivery managed via a Web page as depicted in Figure 5.

CONCLUSIONS

This paper presented recent developments in the Hit2Gap project regarding cloud-based simulation services to improve the operational performance of large estates. The workflow defined for these simulations (i.e. model acquisition, calibration, performance assessment) proved to be adequate to support the development of decision support systems for building operation.

The use of Calibro provides a straightforward and fully automated approach for model calibration. This feature represents a major shift from current practice in the field and provides a long-lasting contribution to the use of simulation in the operational stage of buildings.

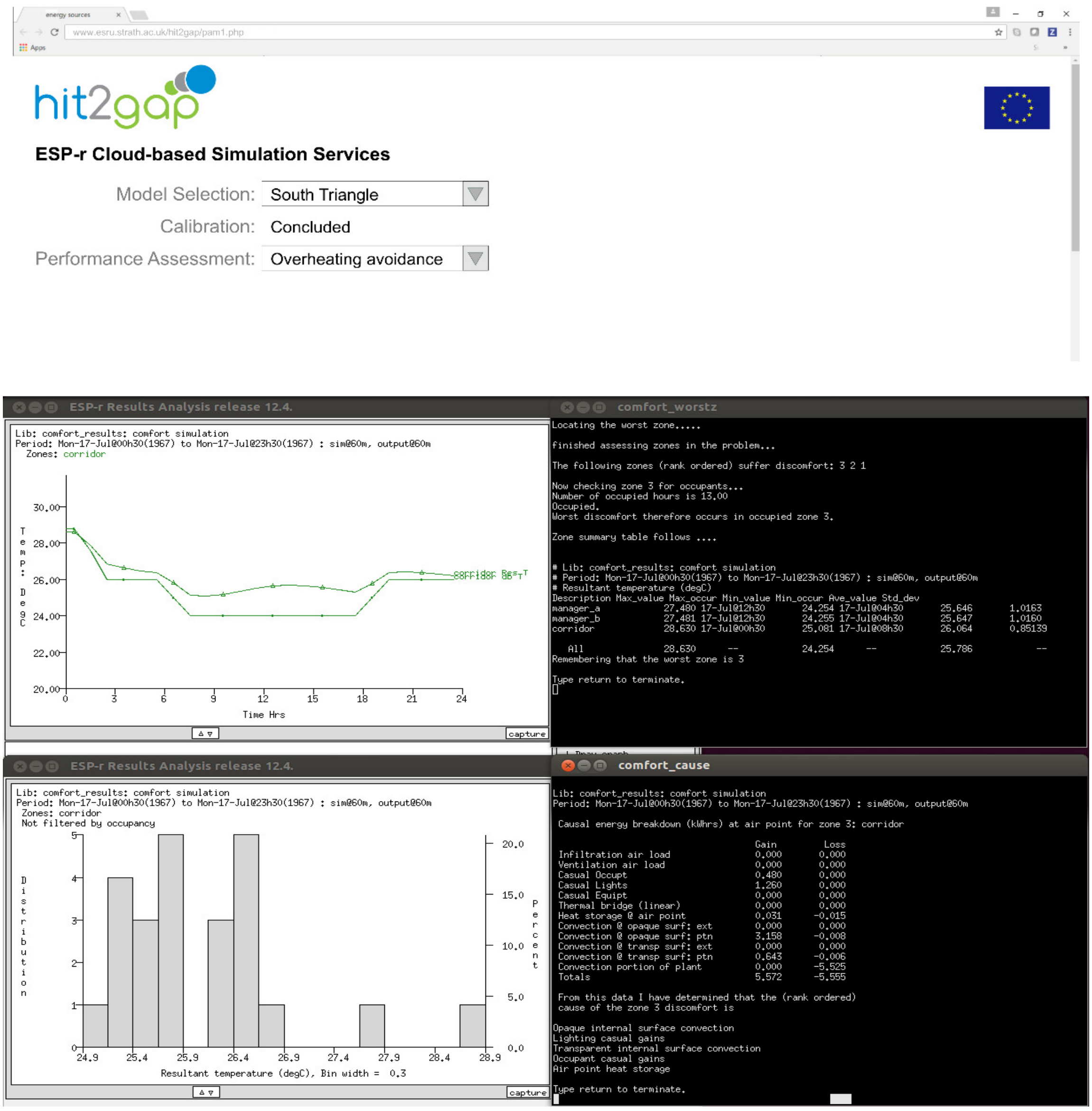

Figure 5: script invocation (upper) and example outcomes from a comfort performance assessment

The use of automatic performance assessment provides access to sophisticated simulation scenarios with minimum user input. The approach does however pose new challenges as it requires the embedding of domain knowledge alongside within simulation procedures to facilitate analysis that supports decision-making. Service users can concentrate on building performance issues rather than expending effort and resources on complex *ad hoc* model calibration and simulation process control.

The openness of the Hit2Gap platform supports the deployment of new simulation services, fostering the development of functionalities and applications tailored to address challenges in the improvement of the operation performance of large estates.

ACKNOWLEDGEMENT

The authors are indebted to colleagues participating in the simulation sub-group of Hit2Gap for their many and varied inputs into the design of the simulation capabilities of the system, and to the Horizon 2020 programme for the resource to undertake the project.

REFERENCES

Bourne S R (1982) *The UNIX System*, Addison-Wesley.

Clarke J A (2001) *Energy Simulation in Building Design (2nd Edition)*, London: Butterworth-Heinemann.

Clarke J A and Hand J (2015) 'An overview of the EnTrak/BuildAX eService delivery platform', *ESRU Occasional Paper O1-2015*.

de Wilde P (2014) 'The gap between predicted and measured energy performance of buildings: A framework for investigation', *Automation in Construction*, 41, pp40–49.

Gelfand A E, Smith A F M and Lee T M (1992) 'Bayesian analysis of constrained parameter and truncated data problems using Gibbs sampling', *J. Amer. Statist. Assoc.* 87, pp523– 532.

Gupta R and Gregg M (2016) 'Empirical evaluation of the energy and environmental performance of a sustainably-designed but under-utilised institutional building in the UK', *Energy and Buildings*, 128, pp68–80.

Herrando M, Cambra D, Navarro M, de la Cruz L, Millán G, and Zabalza I (2016) 'Energy Performance Certification of Faculty Buildings in Spain: The gap between estimated and real energy consumption', *Energy Conversion and Management*, 125, pp141–153.

Hitchin R (2010) 'A guide to the Simplified Building Energy Model (SBEM)', Garston, UK: Building Research Establishment.

Hit2Gap (2015) 'Highly Innovative building control Tools Tackling the energy performance GAP', EU Project ID: 680708.

Hotelling H (1936) 'Relations between two sets of variates', *Biometrika*, 28, pp321–377.

ISO (2013) *ISO 16739 Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries,* International Organization for Standardization, Geneva, Switzerland.

Lawrence R and Keime C (2016) 'Bridging the gap between energy and comfort: Post-occupancy evaluation of two higher-education buildings in Sheffield', *Energy and Buildings*, 130, pp651–666.

Macdonald I A and Clarke J A (2007) 'Applying uncertainty considerations to energy conservation equations', *Energy and Buildings*, 39(9), pp1019-1026.

Monari F (2016) 'Sensitivity Analysis and Bayesian Calibration of Building Energy Models', *PhD Thesis*, University of Strathclyde.

Morris M D (1991) 'Factorial Sampling Plans for Preliminary Computational Experiments', *Technometrics,* 33, pp161–174.

Niu S, Pan W and Zhao Y (2016) 'A virtual reality integrated design approach to improving occupancy information integrity for closing the building energy performance gap', *Sustainable Cities and Society*, 27, pp275–286.

Ossanna J F (1976) 'Nroff/Troff User Manual - CSTR #54', Bell Labs.

Snelson E (2007) 'Flexible and efficient Gaussian process models for machine learning', *PhD thesis*, University College London.

Strachan P, Kokogiannakis G and Macdonald I (2008) 'History and Development of Validation with the ESP-r Simulation Program.' *Building and Environment*, 43 (4), pp601–609.

Wilding M (2013) (viewed December 2016) http://www.bdonline.co.uk/versailles-office-becomes-world%E2%80%99s-first-triple-accredited-building/5049294.article.

Zhao D, McCoy A P, Du J, Agee P and Lu Y (2017) 'Interaction effects of building technology and resident behavior on energy consumption in residential buildings, *Energy and Buildings*, 134.