A 'big data' approach to the application of building performance simulation to improve the operational performance of large estates

Joe Clarke, Daniel Costola, Andrew Cowie, Jon Hand, Nick Kelly, Filippo Monari
Energy Systems Research Unit, University of Strathclyde
Glasgow, Scotland

Abstract

This paper derives from the 'Hit2Gap' project as funded under the European Union's Horizon 2020 R&D programme (Hit2Gap 2015). The aim of this 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 established that is able to collect and store data from disparate sources, and deliver subsets of these data to a range of applications (services) intended to support facilities management. The ultimate aim is to identify physical interventions that will alleviate operational problems and so reduce the performance gap. This paper addresses the role of building performance simulation (BPS) within the Hit2Gap project, specifically: the fetching of an input model, its automated calibration, and its use in scripted applications for HVAC system fault detection and diagnosis, upgrade options appraisal, indoor environment quality improvement, energy demand reduction, renewable energy systems integration and control system refinement. The paper summarises the Hit2Gap architecture, the procedure for the automatic calibration of BPS models, and the invocation of cloud-based performance assessments in response to observed problems.

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, indoor environmental conditions and environmental emissions. Given the uncertainties associated with many model input parameters, it is not surprising that predictions are often substantially different from corresponding observations made at the operational stage (de Wilde 2014, Gupta and Gregg 2016, Herrando *et al*. 2016, Lawrence and Keime 2016, Niu *et al*. 2016, Zhao *et al*. 2017). This performance gap can be addressed by improving the fidelity of the design stage model through explicit consideration of occupant behaviour, the addition of detail in the representation of microclimate, and by incorporating consideration of principal parameter uncertainty at model construction time. In addition, the gap may be further reduced at the operational stage by recalibrating the design stage model using various monitored data types before employing the adjusted model to investigate operational problems and identify remedial actions: this operational stage application is one of the aims of the Hit2Gap project.

At the core of the approach is a cloud-based data platform that supports an open solution to the integration of third party services addressing building facilities management. These services cover a spectrum of possibilities – from the extraction of performance indications from monitored data, through HVAC system fault detection & diagnosis, to energy use forecasting and options for change appraisal – all aimed at improving operational performance and thereby recovering the original design intent. By simplifying the procedure for new service connection, the platform aims to foster initiatives by small and medium sized 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 to a particular service. 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, storing data from measurements and providing basic functionalities (e.g. data anonymization and pre-processing); and
- management level, comprising services that help to improve operational performance.

The aspect considered in this paper is the connection of BPS tools through the delivery of the required input model, its automatic calibration, and its use to appraise options for operational performance improvement. Simulation services are implemented as Web clients hosted by the tool provider for whom the platform provides the means to update services without the need for individual user interaction. For facilities managers and other users, the platform provides the means to access powerful analytic capability with no need to download specific tools and master their idiosyncratic control syntax.

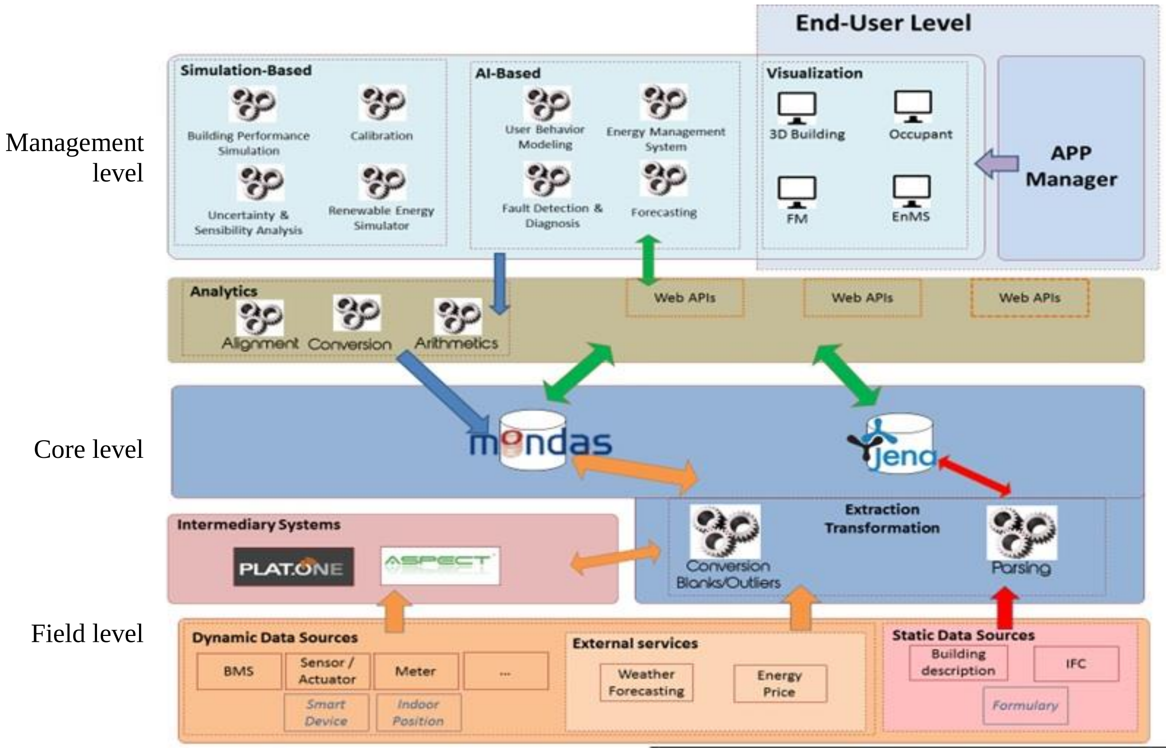


Figure 1: Elements of the Hit2Gap platform (Hit2Gap 2015).

The approach is intended to eliminate conflicting tool versions, facilitate rapid service updating, and support the harmonisation of service application through the adoption of agreed performance assessment procedures and criteria.

As summarised in Figure 2, the delivery of a specific BPS service is a three-step process:

- acquisition, comprising the retrieval of the required input model of a building from 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 determined by performance issues reported by the platform.

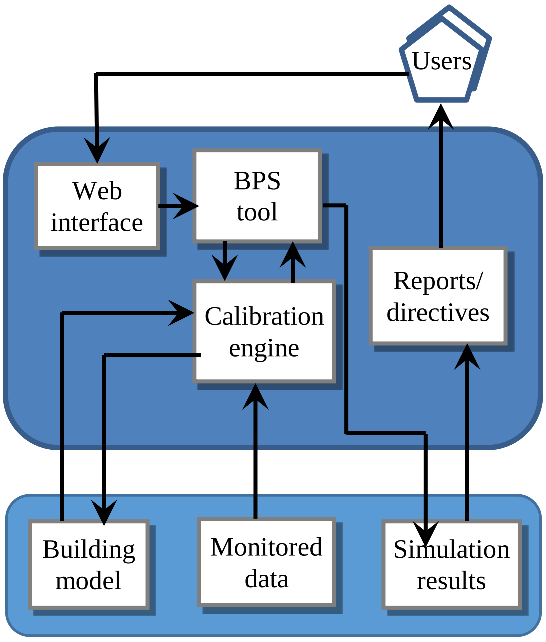


Figure 2: BPS tool interactions.

At present, the platform offers three existing BPS tools, ESP-r, EnergyPlus and REnSIM, used to assess indoor environment, upgrade option and integrated renewable energy system degradation issues respectively; two new tools, GapReasoner and ModSCO[1], for the identification of reasons for any performance gap and HVAC system control appraisal respectively; a non-simulation tool, SBEM, for regulations compliance checking; and a tool that supports the superimposition of performance assessment outcomes on IFC-based building geometry displays. The following sections describe the above three steps.

Acquiring the input model

When a user requests a service, the corresponding BPS 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 as established for another purpose, e.g. a CAD model of building

[1] REnSIM from www.cyric.eu; GapReasoner from www.ise.fraunhofer.de; ModSco from www.nuig.ie.

geometry. 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 as required. The expectation is that this supplement 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 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 corresponding to judicious input parameter 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 targeted output parameters (e.g. indoor conditions, metered energy use *etc*.) and time-matched weather conditions. Using these data, Calibro constructs an emulation (meta-model) 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 utilises four statistical techniques:

- principal components analysis (Jolliffe 2002) to reduce the dimensionality of the input data sets;
- sensitivity analysis (Ratto and Pagano 2010) to select the parameters for emulator inclusion;
- training of the Gaussian process emulator with optimisation techniques (Nelder and Mead 1965); and
- a Markov Chain Monte Carlo method (Rosenthal 2007) to infer the parameter values and related uncertainties.

The best-fit input parameter values are then incorporated in the activated BPS tool's input model before use in performance assessment mode. Further, the differences between parameter values before and after calibration are delivered to the platform as a contribution to an understanding of the causes of the performance gap. It is emphasised that Calibro is BPS tool agnostic and is automated in its application.

Consider the following application of Calibro to two tools intended for significantly different purposes – the ESP-r system 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 Challenger building of Bouygues Construction (Wilding 2013) is modelled (Figure 3, upper). As also depicted in Figure 3, BuildAx multi-sensors (Clarke and Hand 2015) were widely deployed to collected indoor environmental conditions data at 5 minutely intervals, with corresponding weather data acquired from local sources.

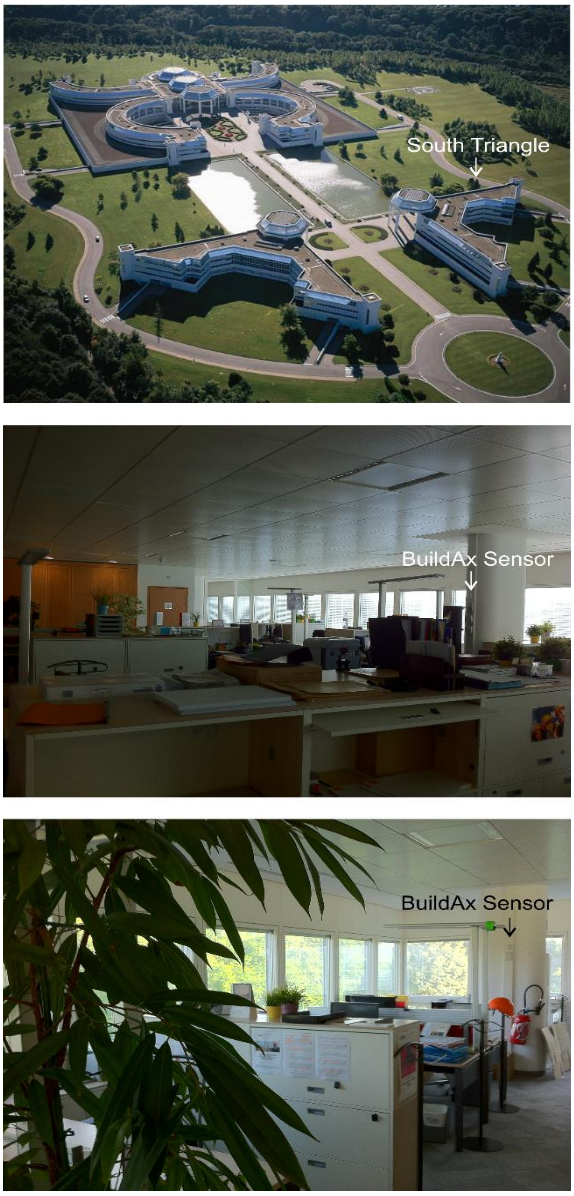
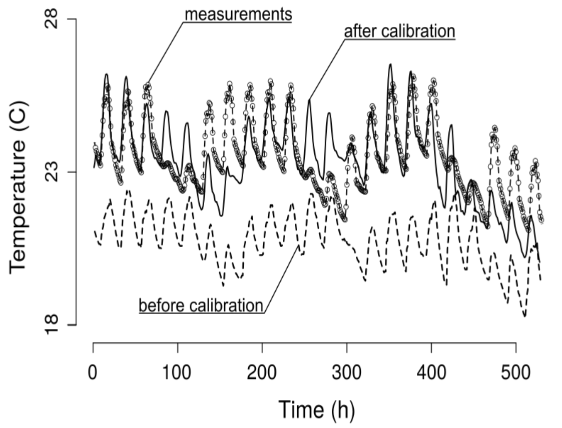


Figure 3: Deployment of BuildAX multi-sensors in the Challenger building.

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, in the case of SBEM, by scripting multiple applications of the tool with parameter increments applied. Figure 4 shows typical outcomes before and after calibration in each case. 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 an operational context.



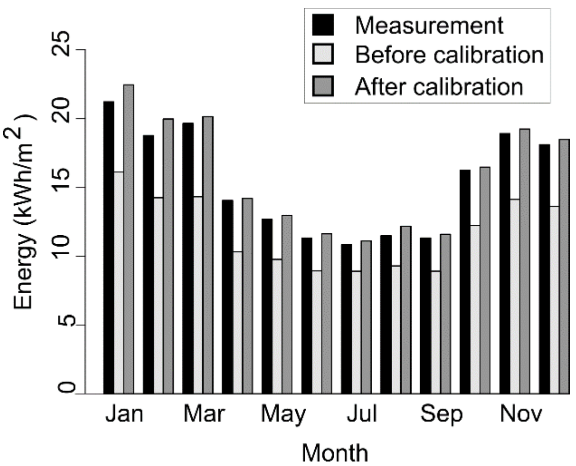


Figure 4: Comparison of ESP-r (top) and SBEM predictions before and after calibration.

Some lessons emerging from the multi-tool calibration activities undertaken to date include the following.

Input-output pair generation: The production of the input-output simulation sets required by Calibro poses considerable challenges as follows.

- The number of required Monte Carlo runs in the above examples was set to 10 times the number of parameters being considered as suggested in the literature (Jones and Schonlau 1998). While reducing this value is computationally desirable, preliminary investigations have indicated increasing problems as the value is lowered.
- In models with few parameters for calibration, Monte Carlo simulations will comprise, at worst, a few hundred runs. In a whole-building, domain-integrated simulation, the amount of input parameters can be substantial: with multiple zones and modelling domains as in the Challenger Building, the number of runs would be of order 10^4 if, unusually, all input parameters were considered uncertain. As each simulation requires several CPU-minutes, the computational burden would be high. One way to reduce this burden would be to use a proxy parameter as described below.
- ESP-r has an in-built parametric sensitivity analysis capability that automates the production of the required input-output pairs. Where such a capability does not exist, it will be necessary to externally script the BPS tool. In this case the quality assurance of outcomes will be problematic as it is difficult to detect errors in simulations when dealing with aggregated data from (potentially) thousands of runs.
- Experience to date indicates that the calibration of complex models is best undertaken incrementally as the model is constructed, as opposed to attempting to calibrate the final, complex model.

Calibration objectives: Model calibration must be purposeful as a model calibrated for one purpose will generally perform badly when applied elsewhere.

- The calibration targets explored to date range from low to high resolution performance aspects such as annual energy consumption and unmet comfort times respectively. While a successful calibration was possible in both cases, applications of the former model showed poor agreement on an hourly basis, while models calibrated against high resolution considerations can perform badly when used for annual energy consumption prediction.
- For cases where time resolution is important, 5 minutely monitored data gave good results when associated with disaggregated energy meter data and the spatial distribution of indoor conditions. At this resolution, Calibro was capable of assessing the model response to rapid changes in internal and boundary conditions although this comes at considerable cost in computational time requiring access to a high performance computer.

Proxy parameters: Many input parameters will vary throughout a simulation, e.g. those with a strong stochastic component, or related to air flow or internal gains. The calibration of such parameters is challenging.

- Where the target for calibration is a prescribed profile (e.g. time varying casual gains or air change rates), it is possible to calibrate the individual values comprising the profile and then assume the calibrated profile thereafter (although this would still result in a large number of parameters for calibration (e.g. 24 hourly values per day type and zone).

- An alternative approach successfully exploited in the Hit2Gap project is to associate a scaling factor with such a profile in a manner that preserves the profile shape. The input-output pairs required by Calibro are then generated based on perturbation of this factor. The suggested value emanating from the calibration effectively nudges the profile to best fit the observation. This approach results in a significant reduction in the number of parameters for calibration. Because Calibro is tool agnostic it makes no distinction between individual input parameters with physical meaning or proxy parameters representing multiple parameters grouped as a profile as long as the variation in the proxy parameter is indicative of the profile it represents.
- Where a domain model exists, for air flow (network- or CFD-based) or stochastic occupant behaviour for example, it is possible to transform the simulation result to a profile and to then apply the scaling factor technique as above. This allows the use of a calibrated profile in place of the domain model but without the need to generate a prescriptive profile in the first place. Further, complex profiles can be decomposed using techniques such as Fourier Analysis or B-Splines, and the parameters corresponding to these harmonics used as the calibration target.
- It may even be possible to apply the above approach where multiple alternative domain models are assumed in the simulations to describe the same problem (e.g. CFD models using different grid resolutions, turbulence models, wall treatments, numerical schemes *etc*.). The results of the proxy parameter calibration can then be used to determine which domain model provides the best representation.

Quality assurance: Deficiencies in models presented for calibration are provided as an interim output from a Calibro analysis to aid model quality assurance.

- Data on the sensitivity between output and input parameters is provided. These data can be used by the modeller to make adjustments to the input-output sets for delivery for final calibration.
- Data on the correlation between calibration residuals and boundary conditions is provided. Such data can help to identify modelling errors, e.g. a strong correlation between solar radiation and residuals led in one case to the identification of problems with the modelling of shading control. The challenge here is to automate such detections.

After calibration, models may be used to undertake performance assessments as long as the calibration target relates to the assessment intention.

Performance assessment

BPS modelling requires significant specialist knowledge. In relation to an assessment of the spatial/ temporal distribution of thermal comfort for example, the modeller is expected to define complex features (e.g. shading operation), process spatially varying simulation time series data, extract relevant performance metrics (e.g. local air temperature, local draught, radiant asymmetry *etc*.), apply acceptable criteria (e.g. PMV between ±0.5), and parse outcomes to relevant design and/ or operational changes. In the Hit2Gap project the intention is to automate such processes so that they may be invoked by users with limited experience with modelling and simulation. The development of such automated performance assessments has three aspects: high-level reasoning that emulates the actions of an informed energy modeller; a scripted process that describes the tool specific steps that automate the assessment; and the reporting of outcomes in terms that may be readily comprehended and acted upon. To these ends a BPS tool's input model must, firstly, 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. These rules are parameterised so that they may be assigned 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.

Consider the thermal comfort performance assessment script shown in Figure 5. Its purpose is to undertake a performance assessment with the following objectives.

- To determine an appropriate weather boundary condition.
- To initiate and control ESP-r simulations for 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 actual assessment comprises several interrelating sub-scripts. The first controls the initial interaction with the platform, requesting the required model and the monitored data (weather and target performance variable) for calibration. The second coordinates the calibration process, including the generation of the simulation input-output sets and the imposition of suggested parameter values on the model. Using the calibrated model, the third invokes the required performance assessment. The fourth combines time series data into relevant comfort criteria and identifies problematic spatial locations. The fifth investigates the cause of discomfort by analysing the magnitudes of the energy flows that comprise an energy balance at the location in question. The sixth commissions a sensitivity analysis to determine possible remedial action. (These last two scripts use the Unix *awk* pattern matching tool to process the extracted simulation data to determine discomfort locations and causes respectively.) The final script gathers all relevant outputs and returns these to the Hit2Gap platform in the required format as follows.

- A technical report summarising the scope and assumptions of the performance assessment and the outcomes obtained.
- Principal findings expressed in terms that readily convey the issues that should be addressed along with recommendations for action in the form of directives for use by the energy management module of the platform.
- The entire simulation results database for possible access by specialists.

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

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

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

The first fragment instructs ESP-r's simulation module, bps, 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 and made from a library of drivers representing the capabilities of the tool.

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.

Such procedures are suitable for implementation on cloud-based computing platforms, with user requests and results delivery managed via a Web page as depicted in Figure 5. Here, the page allows the selection of models known to the platform and their association with one or more cloud-based performance assessment.

Figure 5: Web interface to the ESP-r tool.

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. Three aspects of indoor environmental quality make use of ESP-r application scripting 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. Analysis is carried out based on performance indicators and target values defined by standard BS EN 15251 (overall thermal comfort; BS 2007) and ISO 7730 (local discomfort; ISO 2005). Figure 6 shows an output for a cross-section of a cellular office with two diffusers, one in the centre of the room and one close to the façade on the right.

Operative temperature distribution indicates that the flow rate imposed in the room may be excessive considering the inlet air temperature adopted and the thermal load in the zone, leading to thermal discomfort as temperature values are below the target defined in the standard. Draft rate (DR) results in around 15% of people dissatisfied, a value acceptable but not ideal according to the standard. Other local discomfort criteria defined by the standard can be displayed: (a) vertical air temperature difference between head and ankles, (b) floor temperature and (c) radiant temperature asymmetry. Such an assessment might, for example, lead to a directive suggesting an increase in the air inlet temperature and/or a reduction in the supply flow rate, having also consequences on the building's energy performance.

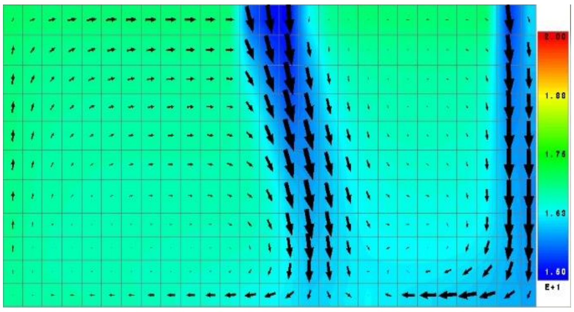


Figure 6: Operative temperature distribution in a cross section of the office.

Visual comfort

This assesses the risk of glare under typical seasonal conditions for standard viewing directions relative to external facades. This necessitates the use of ESP-r's sky radiance model and run-time coupling with Radiance. Performance indicators and target values are defined by standard BS EN 12464-1 (BS 2011). Figure 7, for example, shows luminance values (cd/m^2) for a predefined position, at a predefined critical hour of the year considering the orientation of this façade.

Based on results of this image, the Unified Glare Rating (UGR) was calculated, indicating a value below the threshold defined in the standard, i.e. there is no significant glare risk for the conditions analysed. This result can be used by the facility manager to fine tune the automated controls of blinds, allowing more daylight in cases where risk of glare is negligible (particularly relevant in the Challenger building where users can override the automated control and lower blinds if necessary).

Figure 7: Luminance distribution for a critical hour.

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. As in the previous cases, indicators and target values of CO_2 are defined by the standard BS EN 15251 (BS 2007). Figure 8 shows results for the mean age of air for the same cellular office, indicating age of air below 2 second. Results of CO_2 concentrations are below the threshold for category I of comfort defined in the standard. These results indicate that the recommendations provided by the thermal comfort assessment are robust and a reduction in air flow rates could be applicable to this room, saving fan energy without compromising the indoor environmental quality.

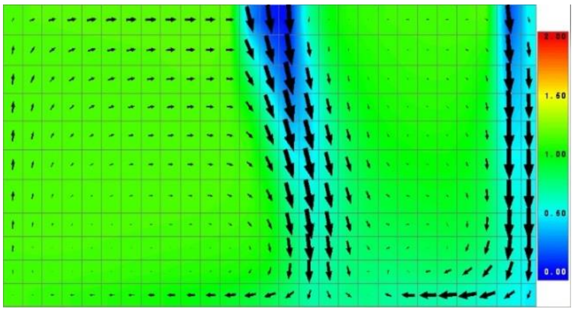


Figure 8: Mean age of air distribution in a cross section of the office.

'Experiential' outputs as depicted in Figures 6-8 are returned to the platform for display via a BIM model visualisation service available as a separate Hit2Gap service[2].

Conclusions

The Hit2Gap project is at the halfway stage and this paper has presented developments to date regarding the connection of cloud-based simulation services to a core data platform as a means to improve the operational performance of large estates. The workflow defined for these simulations (i.e. model

[2] Available from www.zutec.com.

acquisition, calibration, performance assessment) proved to be adequate to support the development of decision support systems for building operation.

The use of a new model calibration tool, Calibro, provides an automated approach to BPS model calibration. This feature represents a major shift from current practice in the field and provides a contribution to the use of simulation in the operational stage of buildings.

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 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 inputs into the design of the simulation capabilities of the system. The Hit2Gap project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 680708.

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