EMBEDDING BUILDING SIMULATION CONSTRUCTS WITHIN FOCUSED APPLICATIONS

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ABSTRACT

Integrated Building Performance Simulation (IBPS) places additional demands on practitioners by requiring them to address diverse technical domains and adopt a multidisciplinary approach to design hypothesis appraisal. Consequently, and as observed by McElroy and Macdonald (2005), the application of IBPS in practice requires a substantial investment in training and adaptation of business procedures. It has also been observed that many organisations apply simulation tools in a focused manner to a relatively narrow range of problems. This paper describes several scope-limited tools based on bespoke interfaces to the ESP-r simulation engine tailored to the needs of non-traditional users of simulation. The contention is that the approach contributes to the improvement of building performance, while exposing users to the potential of IBPS within their familiar business environment.

INTRODUCTION

General purpose simulation tools such as ESP-r (ESRU 2012) can be used by experts to accomplish a range of performance assessments via models of arbitrary complexity. This paper presents an indirect approach to simulation that reduces the resources and skill requirements associated with the direct use of detailed simulation tools. The principal attraction of the approaches is that each can be tailored to the needs of particular user types and applied in ways that are familiar to them.

In common with other simulation tools, such as DOE-2/eQuest (Hirsch 2012) and EnergyPlus (EERE 2012), the simulation engine of ESP-r can be driven by non-human agents, embedded behind bespoke interfaces or employed to generate performance maps from massive parametric excursions. Control agents for ESP-r can be: automation scripts allowing ESP-r modules to be co-ordinated for a given purpose; GUI or Web-based interfaces, which communicate with ESP-r modules via file transfer and remote invocation; and GUI interfaces linked to a fully embedded simulation engine.

The following list categorises the embedded approaches, with examples given in the sections of the paper as stated in parentheses.

The simulator acts as a building emulator for testing Building Energy Management Systems (BEMS) (*Intelligent BEMS*).

Real-time simulation is carried out by linking the simulator to physical sensors/actuators to enable predictions based on currently available measured data in order to influence an actuator signal or raise an operator alert (*Intelligent BEMS*).

The simulator is run over a range of input conditions to develop a performance map that can be embedded in look-up tables, with interpolation where necessary, or to develop a set of correlations by curve fitting (*Housing stock upgrade appraisal, Biomass boiler sizing*).

The simulator is placed behind a constrained interface whereby the user can alter only a relatively few parameters to address a particular design issue (*Control strategy design*, *Natural ventilation*, *Advanced glazing selection*).

The simulator automatically generates simplified models so that a building design can be rapidly compared to a reference design according to prescriptive instructions (*Regulatory applications*).

INTELLIGENT BEMS

Simulation has not traditionally been used for operational building control although the possibility is well recognised. For example, simulation programs have been used in place of a building and its HVAC system to aid commissioning and the training of operators, e.g. the SIMBAD emulator (Husaunndee *et al* 1997). More commonly, simulation is used to evaluate alternative control strategies (e.g. Chua *et al* 2007) and this has evolved to the Building Controls Virtual Test Bed (Wetter 2011) that supports co-simulation between IBPS and control algorithms implemented in Simulink.

Another possibility is to directly embed IBPS within BEMS for use in real-time mode to evaluate control options and make selections in terms of relevant performance measures such as minimum energy use and thermal comfort. Conventional control functions in BEMS have limited or no model of the building and therefore cannot take into account relationships between design and performance parameters. Simulation-assisted control is most suited to control applications with significant look-ahead times (e.g. night ventilation), where there are complex but known system interactions (e.g. glare, requiring blind repositioning, causing luminaire actuation, leading to increased cooling loads), for supervisory control where several alternatives may need to be evaluated (e.g. load shedding), or where the building use varies and is known in advance (e.g. large occupancy variations).

The concept is summarised in Figure 1, which shows the usual BEMS control structure: inputs obtained from weather and building state sensors, with an internal control algorithm deciding appropriate control actions. The new elements are the simulator, which models the building/HVAC using sensed data as boundary conditions; and an evaluator, which scans the simulation results to suggest an appropriate control action to the main simulator-assisted controller.

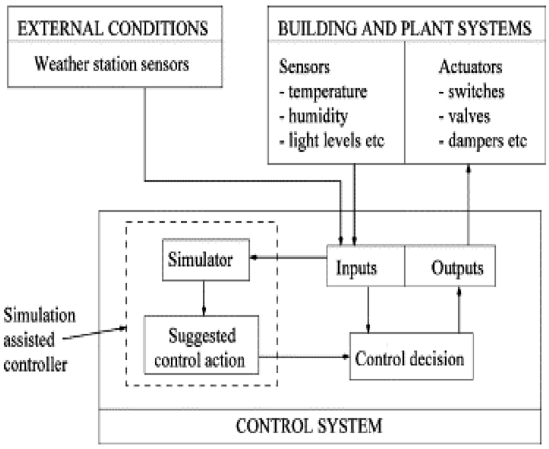

Figure 1: Simulation-assisted control in BEMS.

A prototype control structure was developed and tested in an environmental test room operated by Honeywell at Newhouse in Scotland (Clarke *et al* 2002). Experiments tested the developed controller with realistic time constants. The environmental test facility consisted of two realistically dimensioned rooms surrounded by temperature controlled voids. The constructions used in the test rooms were similar to those in a real dwelling (insulated cavity walls with double-glazed windows) and each room was heated by low temperature radiators supplied from a central boiler. In the study the controller was in optimum start mode.

The GUI allows the user to select from 5 house types, 5 plant types and 5 control regimes (giving a total of 125 variants). For each component in the selected system, individual attributes may be altered. For example, a radiator can have its supply rate, inlet and return temperatures and mass set by the user.

In subsequent studies, involving a comparison of controllers from two manufacturers, a broader comparison of WCH systems was included and coordinated with the manufacturers' test facilities.

CONTOL STRATEGY DESIGN

For rating purposes in the UK, the energy performance of domestic buildings is evaluated using the Standard Assessment Procedure (SAP), which takes a rudimentary approach to assessing the control of heating plant. The impact of the method of control in a house can be significant, and the availability of electronic products with embedded control algorithms creates new opportunities to reduce energy demand. The quantitative energy use and potential savings may be influenced by the type of building construction and heating system, as well as the control logic. Control improvements can be readily applied to existing housing stocks: Palmer *et al* (2006) estimate that 70% of the 2050 housing stock already exists so that a modest reduction in energy use due to better control can make a greater cumulative impact on energy consumption than improvements due to new building standards.

A project was carried out to establish a modelling tool, ADEPT (Advanced Domestic Energy Prediction Tool), for typical domestic house types with wet central heating systems and incorporating a variety of conventional and advanced control approaches. The short time scale dynamics of the control model was integrated into a dynamic construction model with relatively long time constants so that accurate estimates of seasonal and annual energy consumption could be made.

The ADEPT simplified user interface is shown in Figure 2. This facilitates the selection of combinations of house type, heating system and control scheme, with access to a range of system and control parameters including set-points, proportional-integral (PI) control characteristics, and boiler and construction thermal response characteristics. Standardised outputs relating to control system behaviour and energy use are output (Cockroft *et al* 2009) allowing users to evaluate control options in a variety of circumstances, thus taking advantage of the power of simulation while avoiding the learning curve associated with navigating an IBPS system directly.

As an example of tool use, a thermostat controlled radiator system is compared with a system using a PI controller directly modulating the burner. A house meeting current building regulations fitted with a combination boiler was assumed for the comparison. Figure 3 shows the living room temperature control and the water temperatures for the two cases. The room thermostat cycles approximately twice per hour and is set so that the temperature does not fall below 21°C. The PI controller is mostly cycling on/off at the bottom of the modulating range (30%) of the boiler and is able to maintain the room temperature using a lower average water temperature, and run the boiler at a lower firing rate, resulting in an annual saving of 6.2%.

After selecting a building type, the user is able to alter a subset of the model description related to control set-points and parameters. This allows users to concentrate only on aspects of interest while avoiding distractions from other aspects of performance and unintentional changes to other aspects of the model.

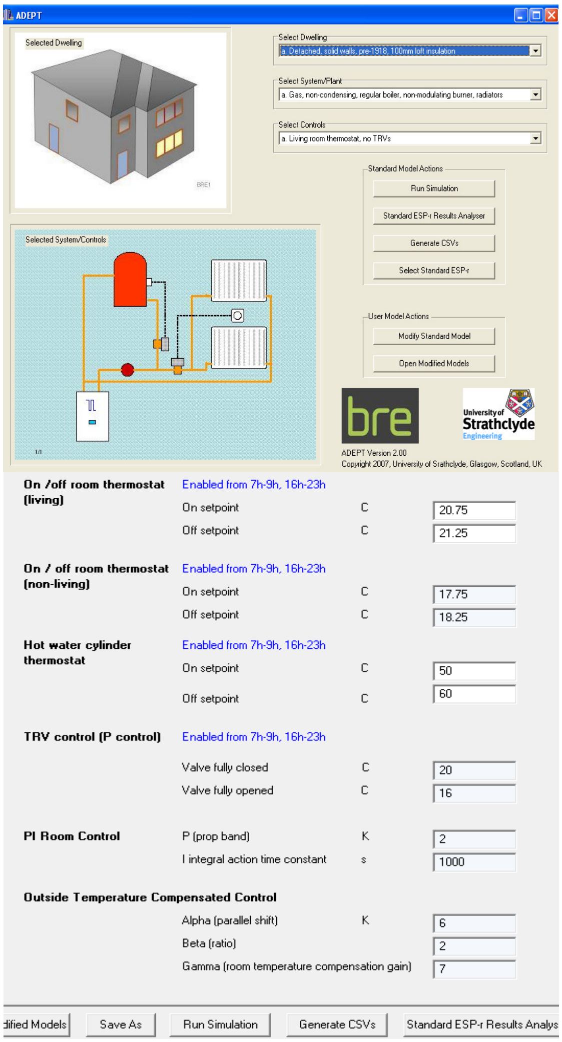

Figure 2: The ADEPT interface.

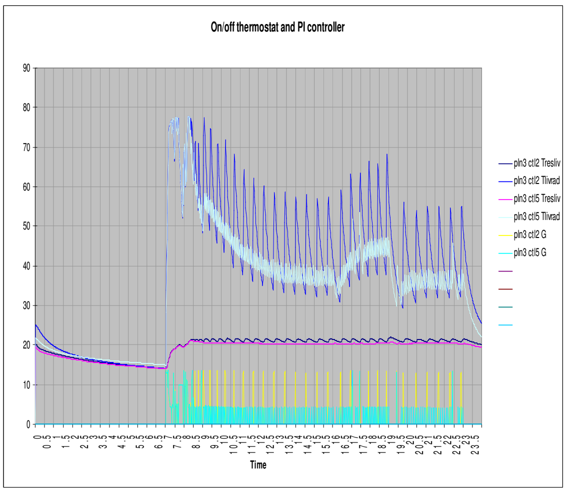

Figure 3: Comparison of on/off thermostat and PI room controller.

ADEPT has been taken up within the controls industry, taking advantage of the accessibility of the interface to demonstrate the benefits of modern controls when compared with existing approaches. The tool is available for download (SESG 2012) and includes the necessary components of the supporting ESP-r distribution.

NATURAL VENTILATION

In the previous example, a focused user interface called upon the simulation tool in a manner that was invisible to the user. Sometimes, just a subset of the simulation capability is required, thus giving direct access to simulation but without the overheads of run-time delays.

A louvre system manufacturer required a sales-oriented selection tool that could assess company products using pre-defined natural ventilation air flow networks processed by a constrained version of the ESP-r mass flow solver.

A specific interface was developed and representative air flow network topologies embedded. For example, Figure 4 shows a stack induced cross-flow ventilation scheme for a three floor building. A range of possible air flow topologies were included including natural and fan-assisted schemes.

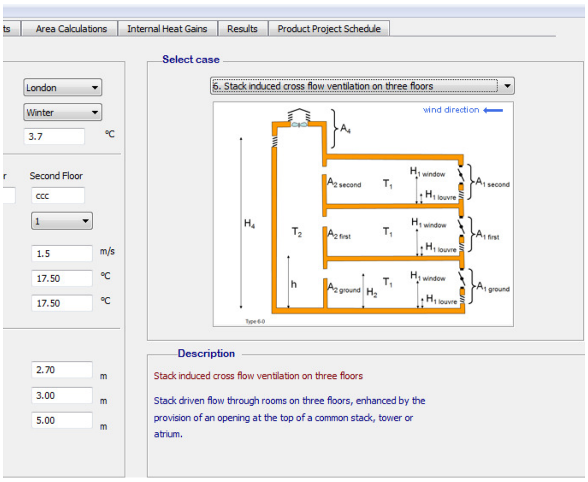

Figure 4: A portion of the ventilation selection tool.

Users can alter temperatures, wind velocity and level of internal gains as well as the height of the louvre. After the iterative solution, the output flow is overlaid on the building cross-section. Rapid adjustments can be made to any particular scheme, with output in the form of a product schedule that may be incorporated into a client offer.

BIOMASS BOILER SIZING

Biomass boiler performance is notably sensitive to oversizing and short-cycling. This project involved the creation of a tool for sizing commercial biomass boilers and their associated thermal storage systems.

A typical strategy is to use thermal storage to minimise the required biomass boiler size (Figure 5). In order to model the charge/discharge process between the boiler and thermal store, the tool needs the hourly heat demand profile for the design day to carry out plant sizing, and the hourly heat demands on other days to calculate the relative contributions of the biomass and auxiliary boilers to meeting that demand.

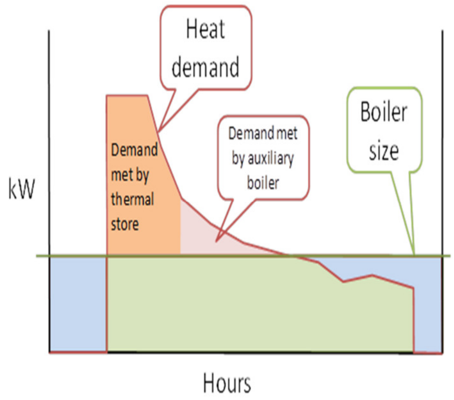

Figure 5: Typical design day head demand profile and boiler size.

In this case it was not feasible to run dynamic simulations in real time and a series of simulations was carried out on a typical building, modelling variations in fabric insulation, fraction of glazed wall area, thermal mass of fabric and duration of occupancy. A total of 81 hourly demand profiles for average outside temperatures ranging from -3°C to 14°C were created. These profiles are then selected from within the tool based on building characteristics defined by the user, with scaling to obtain the actual building profile, and with average daily demand estimated from a method similar to the CEN13790 standard. Further adjustments are made to allow for variations in ventilation loss, casual gains and domestic hot water consumption.

HOUSING STOCK UPGRADE APPRAISAL

Dwelling upgrades are regarded as a major contributor to improving energy performance and carbon emissions. Traditional appraisal mechanisms such as SAP (BRE 2009) and NHER (2012) are based on steady-state and empirical algorithms, which were developed for a narrow range of conditions outside of which their results are questionable. While IBPS is able to address this problem, it is not readily available to policy makers. Moreover, there are no available tools that provide quantitative guidance on the order and type of upgrades that will provide an optimal path in terms of energy demand reduction and efficient resource allocation.

The Housing Upgrade Evaluation (HUE) tool (Figure 6) is based on simulation and provides information on energy, emissions and cost of upgrade measures for the domestic stock. It is based on an extensive set of simulation models that are automatically generated and pre-simulated, with results captured as performance maps.

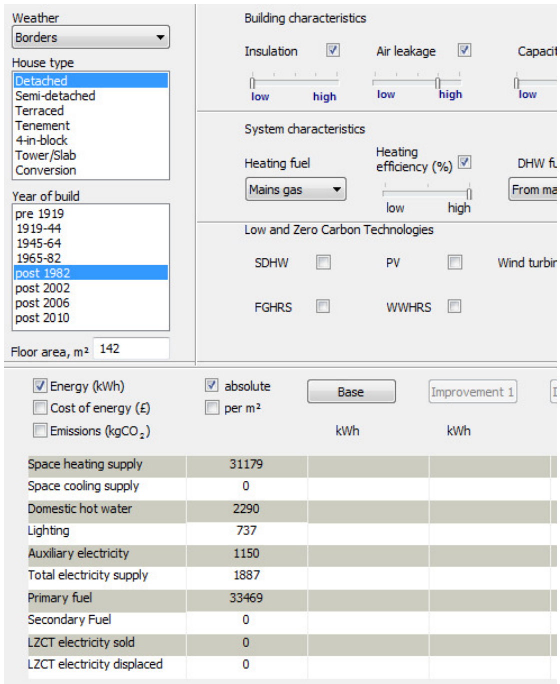

Figure 6: A portion of the HUE tool.

In total some 18,750 prototype models were generated by considering combinations of governing design parameters at quantised levels – exposure, insulation level, air tightness, position of thermal capacity, solar ingress, occupancy level and floor area fractions with different set point temperatures – with parameter values inferred from National House Condition Surveys (Scottish Homes 2009) and the building regulations prevailing at different times. These prototypes were then pre-simulated against weather conditions representative of the UK (75 locations spanning 30 years) and the time series results subjected to a regression analysis to produce equations that express energy demand as a function of weather parameters. These equations are then used as a proxy for the actual simulation results.

Users can determine dwelling energy performance, cost and emissions by answering questions relating to location, built form and year of build. These choices determine a unique prototype based on equivalence rules for the governing design parameters. Additional model detail is inferred from building regulations for the age band and house conditions survey data. The input model can optionally be resolved by adding more detail. Once a dwelling has been selected, it can be improved by choosing upgrades relating to form and fabric and low carbon technologies. This automatically upgrades the dwelling by selection of a replacement prototype. Results for both prototypes are immediately available to the user, who can accept or reject the upgrade based on the impact. The approach may be applied at different scales from a single dwelling to a national housing stock.

HUE has been applied to develop an upgrade plan to 2020 for the Scottish Housing Stock (Clarke *et al* 2004): it was demonstrated that heating energy demand can be reduced by up to 60% by the phased deployment of insulation improvements and air leakage reduction. It has also been applied to provide energy ratings and upgrade advice for individual dwellings (Clarke *et al* 2007) and to assess upgrade strategies for Scottish Local Authorities (Tuohy *et al* 2006).

REGULATORY APPLICATIONS

SBEM, the official calculation tool for generation of Energy Performance Certificates (EPCs) and demonstrating regulation compliance, is restricted in that it can only be applied to non-complex building forms. In order to assess buildings embodying form, fabric and system complexity, the official guidance is to use dynamic thermal simulation tools (BRE 2012). This project involved accreditation of ESP-r for demonstrating compliance with the National Calculation Methodology (NCM; BRE 2010). The NCM imposes constraints on the users of IBPS by prescribing libraries of activities and operational patterns, standard treatments of thermal bridges, standard weather conditions *etc*., and requiring accreditation of programs and users.

Accreditation tasks involved demonstration that results were within specified tolerances (CIBSE 2006) and the automatic generation and simulation of prescribed models. Data input for the models was similar to standard iSBEM but instead of using the SBEM calculation engine ESP-r was employed. Any data that was not provided within the NCM is inferred from building regulations or default values are assumed. This ensures simulation models for buildings of any complexity can be created and assessed for NCM purposes. Once all data has been input, ESP-r follows NCM guidelines and generates the simulation models automatically. These models (Figure 7) are generated according to rules and represent various minimum regulation compliance permutations.

Once generated, the models are subjected to annual simulation and the results post-processed to provide inputs relevant to the creation of energy reports and EPCs.

Another example of this type of application is the NRCAN HOT3000 tool for regulation compliance and energy performance assessment (Purdy *et al* 2005, Canmet ENERGY 2012). This delivers ESP-r simulations through a Web-based interface in which simplified inputs are used to generate simulation models, which are then run to generate the required results.

ADVANCED GLAZING SELECTION

The European Commission's IMAGE (IMplementation of Advanced Glazing in Europe) project (Kristensen 1996) involved the application of IBPS to existing and proposed building designs incorporating advanced glazing systems. To facilitate the wider dissemination of the project's outcomes, a Glazing Design Support Tool (GDST), based on ESP-r, was established to allow the European glass industry to assess the multi-variate impact of applying a given advanced glazing component, to a given building, located in a given climate zone (Figure 8).

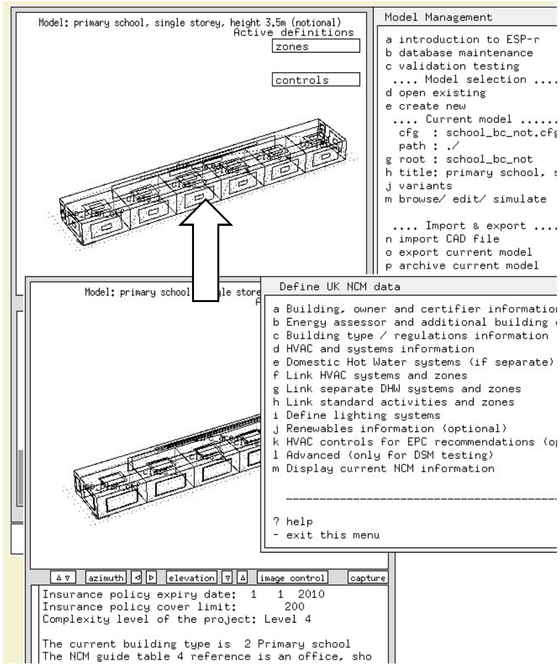

Figure 7: NCM interface in ESP-r showing initial and morphed models.

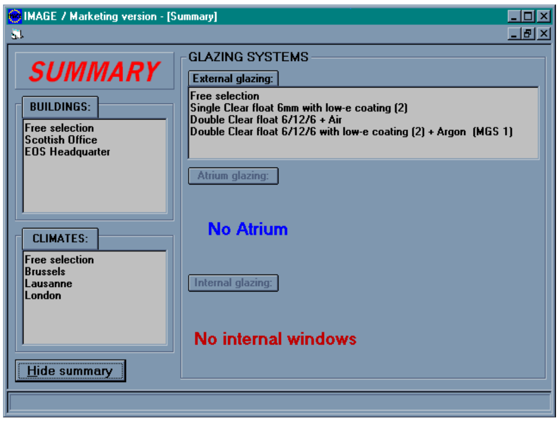

Figure 8: The GDST interface.

GDST stores ESP-r models of exemplar and project-specific buildings, weather data relating to typical and project-specific climates and data defining the optical and thermal properties of advanced glazing components. In use, it allows association of glazing components with buildings and buildings with climates, and the retrieval of pre-formed, multi-variate views of performance (encapsulating energy use, gaseous emission and thermal/visual comfort aspects) for pre-selected combinations of building, climate and glazing. It is possible to invoke ESP-r for combinations not previously processed, or for the analysis of new glazing components.

DISCUSSION

The Open Source license of ESP-r allows third parties to adapt the system to support specific project goals and for others to subsequently learn from and extend embedded simulation facilities.

The rapid evolution of ESP-r is in part a result of diverse and distributed development groups making use of the platform to further their separate goals. Evolution is, of course, matched with a rigorous testing regime and a messaging facility which ensures that all members of the international development community are apprised of changes as they happen.

One strength of the embedding approach as discussed in this paper is the range of computing platforms which can be utilized. For example, the management and production of the many prototype models and assessments used in support of the Windows-based HUE tool were carried out on a Linux compute-cluster.

As is clear from the above figures, the style of GUI in agents has evolved over time. This reflects changes in graphic tool-kits as well as preferences at the time the tools were created. In some cases the GUI needed to take a recognizable form – the HUE tool, for example, mimics the layout of the SAP interface. In the case of the natural ventilation tool the client specified the range of room arrangements and the attributes of the louvers and openings that they wished to explore.

The GDST tool's focus on windows made use of a performance look-up of the most common set of glazing distributions. If the user selected a combination which was unknown then the closest base model was adapted and an assessment commissioned. This required knowledge of the type and distribution of windows within a fixed number of models and then a systematic find and replace facility as well as a mechanism to pass back the relevant performance data to the GUI. The approach reduced the scope of the initial parametric study and allowed an expansion route for unforeseen 'what if' studies to be implemented with little or no impact on the GUI.

The addition of compliance tasks to ESP-r involved extending the data model, adding new user interactions as well as automating the creation and assessment of prescribed building variants. ESP-r looks essentially the same but the actions of the users are constrained. When running in compliance mode some aspects of the solution process are disallowed, for example ESP-r's air flow network, CFD and RADIANCE co-simulation features are disabled.

For Windows-based GUIs Visual Studio was used for most of the projects while Borland C++ was used for ADEPT. ESP-r is usually compiled with the GNU compilers (gfortran, cc, c++) on all computing platforms with an option to build the simulation engine as a dll.

For accessing data from prior parametric studies, the GUI will typically create a unique identifier for the combination of attributes under consideration and then recover the relevant performance of that specific combination from a database.

Where real-time assessments are required, the combination of attributes is matched to an existing ESP-r model and a temporary copy created and then transformed via editing of the model files. The modified model is then used for assessment and disposed of at the end of the session.

In other implementations, the background work for the GUI agent is carried out by standard ESP-r modules based on command scripts generated by the agent. Embedded simulation based on command scripting is, however, sensitive to the evolution of the ESP-r interface and command syntax. For example, the re-ordering of options in a menu can break a script.

Some third party tools are also keyed to a specific version of ESP-r. This will be problematic where sufficient resources are not available to include a regular update cycle of the GUI in order to take advantage of newer versions of the simulation tool.

CONCLUSIONS

While IBPS is a powerful design tool, it places a considerable burden on those who wish to apply it in the time and resource constrained environment of design practice. Focused, simulation-based tools are therefore perceived by many as an interim solution until the profession can put in place a more effective support framework for IBPS deployment than exists at present. This paper has described several instances of the approach based on the simulation engine of the ESP-r system.

ACKNOWLEDGEMENTS

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