A simulation-based procedure for the holistic resilience testing of building performance

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Abstract. The design of an energy efficient urban environment is a formidable task because the underlying processes are complex, coupled and time varying. Competing objectives from a variety of stakeholders relating to occupant wellbeing, fuel poverty alleviation, improved air quality, low energy use, emissions reduction, and legislative compliance then act to confound the attainment of operational quality and resilience of particular design solutions. This gives rise to a persistent and growing gap between design intent (in both new build and retrofit contexts) and the operational reality. Unfortunately, there are no current standards for building performance appraisal and operational resilience testing so that such assessments, where undertaken, are ad hoc and implemented as an arbitrary function of the particular project context. The result is that it is impossible to compare alternative proposals in terms of the performance that is likely to be delivered in practice. This paper reports recent developments in automating the application of building performance simulation as a means to address this deficiency.

1. Introduction

The drive towards a more sustainable built environment gives rise to challenges for construction industry practitioners. From an energy viewpoint, these challenges stem from the need to reduce energy consumption, integrate sustainable energy supplies and mitigate environmental impacts, all while meeting expectations for human wellbeing and economic growth. The design of an energy efficient building or community is a formidable task because the underlying physical processes are complex: coupled heat and mass transfers, possibly bidirectional electrical power flows, radiation exchanges, distributed control actions, uncertain occupant behaviours and equipment failures, all of which vary spatially and temporally.

The design task is then confounded by myriad policy agendas aimed at stimulating a clean energy transition through accelerated renewables deployment and the electrification of building heating and transport. Such policy goals usually give rise to competing aspirations relating to occupant satisfaction, fuel poverty alleviation, local air quality improvement, energy demand reduction, emissions abatement, energy supply resilience, and more stringent legislative compliance. Because of this socio-technical complexity, the gap between design intent and the operational reality is both persistent and growing [1] [2]. This paper reports on a simulation-based procedure that provides a means to address this gap.

In relation to reducing the energy demand associated with the built environment, there are many competing technology options including, but not limited to, those listed in Table 1. Such options are typically unable to provide an effective solution on their own and in many cases may be mutually
exclusive. The need then is to identify fit-for-purpose blends as a function of the requirements and constraints of a particular scheme. This is an obvious role for Energy Systems Simulation (ESS), a term used hereinafter to refer to building performance simulation when applied to buildings and their related energy supply systems within the urban environment at whatever scale. ESS probably provides the most effective mechanism to identify appropriate solutions within the time and resource constraints of design practice.

Table 1. Example energy demand reduction options.

| Passive features       | Heat-related                  | Electricity-related       |
|------------------------|-------------------------------|---------------------------|
| daylight utilisation   | heat pumps                     | integrated photovoltaics   |
| adaptive facades       | solar thermal                  | smart meters              |
| solar ventilation pre-heat | electricity-to-heat           | smart grids               |
| switchable glazing     | condensing boilers            | urban wind power          |
| selective films        | smart heating control          | fuel cells and hydrogen   |
| advanced insulation    | heat recovery                  | electric vehicles         |
| desiccant cooling      | biomass/biofuel heating        | demand management         |
| evaporative cooling    | culvert heating/cooling        | demand response           |
| moveable devices       | district heating/cooling       | smart water heating       |
| breathable walls       | energy storage                 | combined heat/ power      |
| phase change materials | tri-generation                | ducted wind turbines      |

Less obvious, but no less powerful, is the use of ESS to ensure the best temporal match between energy demand and energy supply as derived in the latter case from appropriate blends of conventional (fossil fuel and nuclear) and renewable (national and urban scale) energy technologies assisted by energy storage and/or utility grid interaction.

The conflicts that underlie policy and business agendas that seek to electrify building heating and transport, to encourage net zero energy in the housing stock, to establish community energy schemes via smart control, or encourage urban renewables, can best be resolved by utilising this dynamic matching capability to design hybrid schemes. Examples of such conflicts include the tensions between cost reduction, occupant wellbeing, fuel poverty, indoor/outdoor air quality, real-time utility transactions and so on. The merits of an ESS approach that enables whole system, multi-variate performance appraisal under realistic operational scenarios are summarised in Table 2. It is likely that no other approach can accommodate the underlying physics while addressing all relevant performance aspects and satisfying the time and cost constraints of business – or as succinctly summarised by Hong et al [3]: “Building simulation serves not only to reveal the interactions between the building and its occupants, HVAC systems, and the outdoor climate, but also to make possible environmentally-friendly design options”.

Table 2. Merits of the ESS approach.

| Can address all relevant issues:                      | Can encapsulate all relevant processes:                          |
|------------------------------------------------------|-----------------------------------------------------------------|
| technical feasibility;                                | building physics;                                               |
| thermal and adaptive comfort;                         | thermo-fluids;                                                  |
| indoor and outdoor air quality;                       | heat and mass transfer;                                         |
| life cycle operation;                                 | radiant heat exchange;                                          |
| energy and carbon economics;                         | plant and systems processes;                                    |
| environmental emissions;                              | electrical power flows;                                         |
| controllability assurance;                            | micro-climate;                                                 |
| operational resilience.                               | renewables stochasticity;                                       |
| wellbeing and productivity;                           | control system response;                                       |
| uncertainty and risk;                                 | innovative materials and systems;                               |
| increasingly stringent legislation                     | stochastic events.                                              |
Towards SBE: from Policy to Practice

The projects reported in this paper seek to standardise performance assessments in relation to the resilience testing of new designs and retrofits. Currently, there is no standard way to assess building performance in a manner that addresses lifetime resilience. These projects aim to create industry standard performance assessment procedures that require no specialist knowledge of any particular modelling tool on the part of the user.

The overall message of the paper is that clean energy transition aspirations have fostered conflicting technology solutions that are not generally applicable. Holistic performance simulation is one way to select appropriate solutions for specific contexts, ensure operational resilience and reduce the gap between design intent and performance in use.

2. EES theoretical basis
To deliver such functionality, ESS requires high resolution models, implying a profound departure from traditional approaches to design appraisal [4] [5]. All energy systems – heat pumps, buildings, district heating, photovoltaic panels etc. – have 4 characteristics that need to be preserved where the aim is to enable an emulation of reality. First, they are intrinsically dynamic due to the spatially distributed heat, mass and momentum exchanges that vary with time and at different rates. Second, defining data (e.g. material thermo-physical properties and plant efficiencies) are non-linear in that they vary as a function of the evolving variables of state (e.g. temperature and moisture content). Third, the system overall is systemic in that component parts impact variously on capital & running cost, thermal & visual comfort, emissions & air quality, electricity network interactions & power quality, and controllability & resilience. Fourth, some principal influences are stochastic in that they derive from uncertain processes associated with occupant behaviour, weather and equipment failure.

Where one or more of these characteristics are overly simplified, the resulting ESS tool will reduce to a mere calculator that, seemingly by design, is misaligned with the reality. Within high integrity ESS, there is no justification for imposing actions such as, for example:
- representing constructions dynamically but plant components in steady-state;
- representing infiltration and ventilation via imposed air change rates when flows depend on time varying pressure and temperature differences;
- prescribing equipment efficiencies when these depend on the as yet unknown values of state variables (such as the dependency of a heat pump’s coefficient of performance on evaporator and condenser temperatures, which may be highly variable); and
- decoupling system parts as a computational convenience.

As summarised by the collage of Figure 1, the ESS numerical approach conserves energy, mass and momentum within connected finite volumes corresponding to a discretised equivalent of some energy system at whatever scale and when subjected to heat transfer mechanisms, sources of the conserved properties, and control actions.

Even with such a high resolution approach to performance simulation, it is hubris to suggest that it is possible to predict the future state of a system. Instead, the aim is to emulate reality as a means to ensure operational resilience. This is achieved by ensuring that the causal relationships between different aspects of a system are explicitly represented. For example, to test the acceptable performance and resilience of a community energy scheme utilising building-integrated photovoltaic (PV) components and interactions with the low voltage electricity network (LVN), several couplings would need to be represented, such as:
- increased daylight penetration to indoor spaces (needs daylight modelling);
- resulting in artificial light dimming (needs photocell modelling);
- giving rise to a reduced electrical load (needs power flow modelling);
- requiring the power flow from a local PV array to be exported (needs PV cell modelling);
- perhaps resulting in a power quality impact on the LVN (needs network modelling);
- requiring an export refusal or tariff adjustment (needs utility control modelling); and
- necessitating an alternative dump load for the PV power (needs storage modelling).
Such a simulation would result in an entirely different outcome than one that merely determined the output power from the PV array for a given irradiance with no consideration of system interactions; and would lead naturally to a robust practical scheme that is more likely to perform as required when established.

**Figure 1.** The ESS numerical approach.

### 3. High resolution modelling

The use of ESS for future reality emulation requires a high resolution input model [6]. Figure 2 shows such a model for a dwelling.

**Figure 2.** A high resolution house model.

This model comprises all relevant physical entities – 3D form, construction material attribution, internal fittings & furnishings, heating system & hot water components, low voltage electrical network,
solar thermal panel (could be PV), and control system components. To such a model must be added (automatically where possible) virtual constructs relating to network air & electricity flow, room air movement, gas boiler combustion-related emissions and occupant behaviour. Such a model is capable of providing a range of relevant outputs addressing the different aspects of overall performance, such as the snapshot examples depicted in the collage of Figure 3.

Similar high resolution models can be created for the non-domestic case where data defining form, fabric and contents are augmented by descriptions related to occupant presence, control systems, HVAC equipment, renewable energy components, artificial lighting and electrical networks. In this case, outputs can, additionally, include the spatial and temporal distribution of thermal comfort, discomfort glare and indoor air quality (as evaluated against any relevant standard) as depicted in Figure 4.

**Thermal comfort – ISO 7730**  
• PMV  
• draught risk  
• vertical air temperature stratification  
• floor temperature  
• radiant asymmetry

**Visual comfort – BS EN 12464-1**  
• glare related to daylight  
• unified glare rating, UGR ≤ 19

**Air quality – BS EN 15251**  
• $CO_2$ concentration

**Figure 3.** Some possible outputs from a high resolution dwelling model.

**Figure 4.** Wellness outputs from a high resolution office model.
Two features of the high resolution modelling approach are emphasised here. First, the approach is holistic and therefore enables performance to be represented in terms of a range of relevant criteria. Second, it is possible to semi-automate the generation of models for large building stocks based on design parameter diversification applied to ‘seed’ models corresponding to particular archetypes [7]. The former feature provides a means to make trade-offs explicit (e.g. between energy reduction and occupant wellbeing); the latter feature reduces the model creation burden and helps harmonise the simulation process because the same model can be utilised by different users and for different applications.

4. Resilience testing

While the analysis capability of EES covers an extensive range of performance aspects, the technology is not particularly easy to apply in practice. One approach to alleviate this dilemma is to adapt the manner in which simulation is accessed by providing cloud-based services offering industry standard performance assessments. Imagine a future in which simulation services exist that:

- operate on the basis of design proposals delivered as high integrity BIM models [8] (extensions to current data schemas will be required to cover all descriptive and performance domains covered by ESS in future);
- require no user involvement in the simulation process;
- automatically initiate standard performance assessments;
- evaluate the performance outcomes against agreed criteria;
- judge overall acceptability using models of building users/operators (as opposed to simulation tool users as now); and
- facilitate the unambiguous comparison of alternative proposals.

This is the approach adopted in the Horizon 2020 Hit2Gap [9] and Construction Scotland Innovation Centre (CSIC) Resilience Testing [10] projects; the former nearing completion, the latter recently commenced. Figure 5 summarises the concept.

Figure 5. A cloud-based resilience testing service powered by an approved ESS.

The aim is to standardise and automate performance assessments corresponding to different design targets – low energy dwellings, estate facility management, community energy schemes, critical environments in the health service etc. – and levels of test stringency, e.g. current regulations, Passivhaus standard [11] or net-zero energy in the case of housing.
Within the Hit2Gap project, automated simulation services are targeted on the energy and wellbeing aspects of facility management within large estates. Within the CSIC project, the focus is building design and refurbishment, with several companies led by CIBSE and RIAS collaborating to establish performance assessment procedures, assessment criteria and resilience impacting events for different building types. The outcomes are encapsulated within a ‘Resilience Testing Environment’ prototype (Figure 5), which is being field trialled within live projects at different scale.

Such emulations of reality, have significant benefits. Assuming that they include a realistic representation of occupant behaviour (e.g. [12]), they relate more closely to reality and not to an inappropriately simplified, partial representation. They do not require the simulation tool user to define performance assessments and interpret outcomes, thus standardising the assessment process and facilitating the inter-comparison of alternative proposals in terms of whether or not they passed the test. Such attributes leave the design team free to innovate, supported by a computational environment that assures acceptable performance under a range of conditions likely to be encountered in practice, and in terms of performance criteria that can be readily understood by different stakeholders. The approach also provides a mechanism for building regulation compliance that overcomes the constraints of the present rudimentary methods that fail to respect the thermodynamic integrity of contemporary and future energy systems. (It is emphasised here that simulation models may still be configured against standard prescriptions in order to obtain outputs from simulation tools for legislative compliance purposes, to size system components for peak demand, or to obtain deeper performance insight – i.e. the traditional application of simulation techniques.)

At the present time, the simulation environment depicted in Figure 5, when powered by the ESP-r system [13], has been connected to the BEMServer platform as established within the Hit2Gap project [9] and is being field trialled by application to two pilot buildings. Within this implementation, pre-constructed, high resolution models are automatically calibrated using the Calibro application [14] prior to being subjected to requested performance assessments that are entirely automated. At the same time, an industry consortium led by CIBSE has been established within the CSIC project [10] to harmonise approaches to performance assessment in support of building design and identify the ‘gremlins’ that might be randomly applied during resilience tests to ensure the robustness of outcomes.

5. Conclusions
Explicit performance simulation provides powerful support for the identification of effective energy-related actions within the built environment. Hitherto, the potential of the approach has been hampered by the lack of standards relating to the assessment of proposals in a manner that ensures resilience in operation and facilitates direct comparison of alternative proposals.

This paper has reported two projects that are researching the concept of a simulation-based environments that automatically apply standardised performance assessments to proposals and provides a means to issue compliance certificates corresponding to increasing levels of resilience stringency. This is an approach which, it is hoped, will bring benefit to design practitioners, policy makers, estate managers and researchers because it harmonises the use of performance simulation in practice as a means to explore dynamic behaviour over a proposal’s lifetime in order to reduce the performance gap.

The use of automatic performance assessment provides access to sophisticated simulation scenarios with minimum user input required because the approach incorporates assessment knowledge alongside simulation tool control. Service users then can concentrate on improving building performance rather than expending effort and resources on complex ad hoc model calibration, simulation process control and results analysis.

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