Data requirements of high resolution models to confirm retrofit package efficacy within the INDU-Zero project

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Preamble

Integrated building performance simulation can improve building design by allowing comprehensive appraisals under realistic operating conditions. Figure 1 summarises the process as conceived within the INDU-Zero project to employ the method to confirm the effectiveness of any proposed upgrade and deliver a digital model for use in factory equipment programming to produce upgrade components.

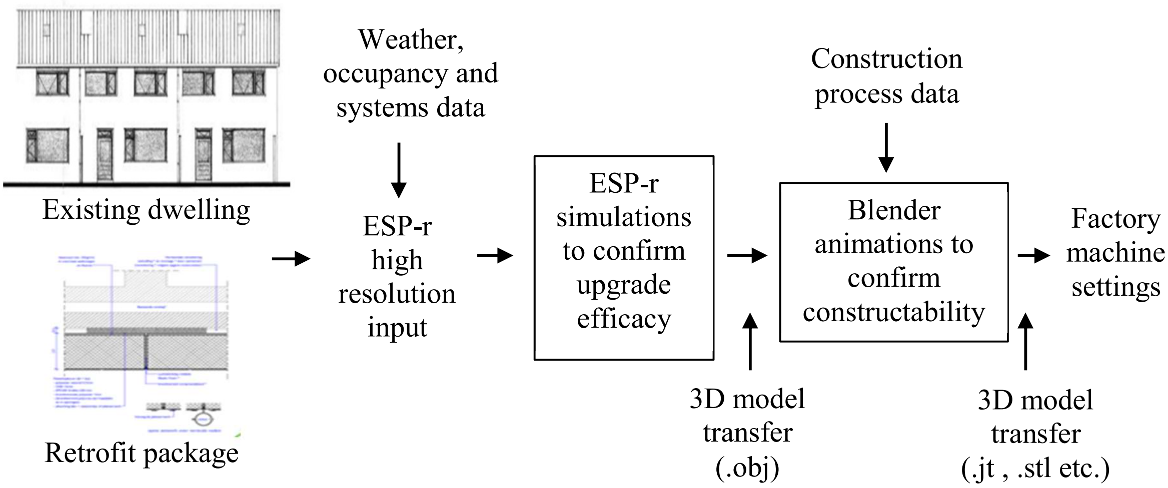

Figure 1. The INDU-Zero upgrade evaluation and data supply chain.

The process commences with the sourcing of design details for dwellings deemed representative of the estate being targeted for renovation, and the use of this information to construct a high resolution model to confirm, by rigorous simulation, that the intended performance improvements are likely to materialise in practice. This document identifies the non-trivial issues involved in sourcing these details.

High resolution modelling

The data types required to construct a high resolution model of a dwelling are many and various covering aspects such as: weather time series; 3D geometry; hygro-thermal properties of construction materials; thermal bridges; air flow path distribution; internal thermal mass locations; operational details (occupancy, lighting and small power); heating, ventilation and domestic hot water systems; embedded renewable energy components, and control systems. Typically, the collection of such data will require a significant effort and its collation will be hampered by different source formats such as construction drawings, manufacturer's data sheets, standards requirements at the time of build, national house conditions surveys, specific site surveys and, exceptionally, in digital form (e.g. partial BIM, PHPP spreadsheet etc.). As the depth of information available increases, Table 1 summarises the cumulative enhancement of a high resolution model then enabled and the performance assessments that will follow.

Table 1: cumulative data needs of a high resolution model.

Problem description	Performance assessment enabled
building regulations	simple performance indicators (e.g. U-value)
+ geometry	visualisation, photomontage, shading
+ constructional attribution	material quantities, embodied energy
+ operational attribution	casual gains, electricity demands
+ boundary conditions	illuminance distribution, no-systems comfort
+ special materials	photovoltaic components, switchable glazing
+ control system	daylight utilisation, energy use, response time
+ flow network	ventilation, heat recovery evaluation
+ HVAC network	psychrometric analysis, component sizing
+ CFD domain	indoor air quality, thermal comfort
+ electrical network	renewable energy integration, load control
+ enhanced resolution	thermal bridging
+ moisture network	local condensation, mould growth, health

An initial, modest effort by a model builder – say examining building regulations at the time of dwelling construction – can indicate aspects such as insulation standard and air tightness. Acting on such insights, an initial model might be prepared to enable building performance refinement without recourse to energy consuming plant and systems: daylight capture might be explored as a way to displace the electrical power associated with artificial lighting, or various approaches to direct solar capture and passive utilisation might be considered. After the 'no-systems' performance of the building has been refined, an environmental control system can be introduced and 'tuned' to achieve efficient operation as loadings vary; this will typically require the extension of the data model to include building air leakage and pressure distribution, plant components and control system parameters.

It is at this point that conventional modelling is left behind and the potential of high resolution modelling becomes apparent. A representation of the building's electrical network might be established to assess the impact of active demand management on the feasibility of utilising local energy sources (through heat pumps, photovoltaic components, micro wind turbines and the like), or to explore the demand/ supply match over time when such technologies are deployed in alternative configurations. Having arrived at a robust technical solution, individual spaces within the building might be further discretised to allow an assessment of indoor comfort and air quality.

While many models are built to represent the geometrical aspects of a building, an integrated data model must cover all aspects of building representation – from geometry, construction and operation, through HVAC systems and control, to new and renewable energy systems. A high resolution model permits the pre-deployment confirmation of the efficacy of any proposed dwelling upgrade in terms of cost and performance parameters relating to energy use, indoor conditions and environmental impacts as depicted in Figure 2. This is the best way to ensure that energy targets are attained in practice but not at the expense of other important performance aspects.

New data types required

The fundamental data requirement of a high resolution model relates to building geometry and construction and is well understood. Table 2 lists the data requirements of 4 technical domains as required to enable the performance assessment functionality listed in Table 1 but not traditionally included in a model. These correspond to network air flow, computational fluid dynamics, lighting simulation and electrical networks incorporating renewable energy systems.

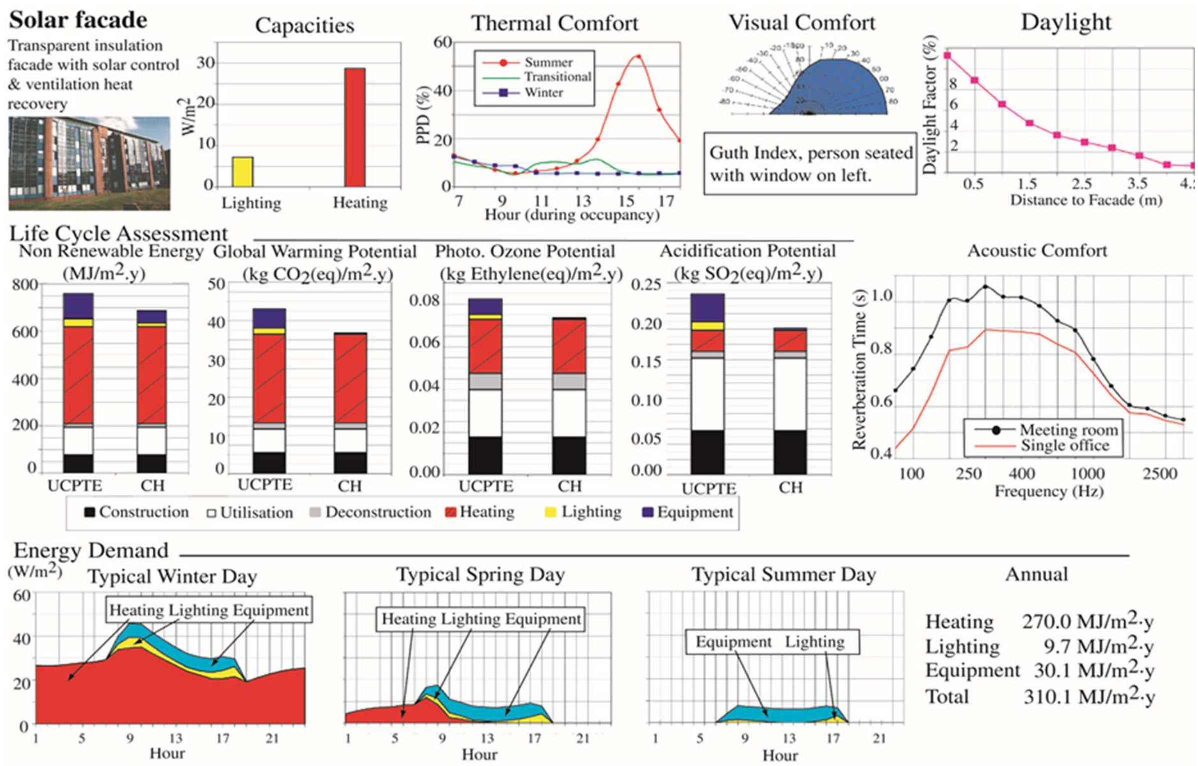

Figure 2: An integrated view of performance.

Network Air Flow

Thermodynamic forces cause energy to flow around a building and, through conduction, convection and radiation, energy is gained and lost to the external environment. Dynamic simulation models replicate these energy flows and the many thermodynamic processes that are involved. Traditionally, air flow withing a building was often treated as a non-dynamic element and represented as prescribed air change rates. This approach is a throwback to manual calculation methods, and finds its way into various calculation tools as a means to avoid the necessity of constructing data models to describe network air flow dynamically. The result is a loss of similitude to real buildings. Air flows result from the interactions between external wind pressure, buoyancy due to temperature differences, the operation of plant items, and the interaction of occupants with ventilation control devices. All these forcing effects can demonstrate high temporal variability, and the resulting building behaviour often diverges markedly from that which assumes steady-state conditions for these variables.

The data required to model dynamic air flow fall into four main categories as follows.

1. Boundary condition determinants – e.g. external air speed and direction, vertical velocity profile and turbulence and external pressure coefficient distribution. Weather data and environment descriptors can be used to create suitable driving force information, while pressure coefficient data for simple building shapes are available. In the past, more complex geometries required a wind tunnel studies to be undertaken, but now computational fluid dynamics codes are used for this purpose.
2. Generic flow resistances – e.g. cracks around windows, doorways, fixed louvres, ductwork and fittings. Formulae describing the non-linear behaviour of such components along with

coefficient values are generally available from the literature., while the flowpaths themselves can often be inferred from the building geometry.
3. Ventilation control devices – e.g. fans and adjustable louvres. Manufacturers of such products can usually provide the necessary flow relationships.
4. Occupant behaviour descriptions – e.g. window opening patterns, which may be linked to an occupant behaviour modelling scheme.

Dynamic air flow modelling, integrated into the overall building thermal simulation, allows a range of typical building performance behaviours to be investigated. Any building that is naturally ventilated, or relies partially on natural ventilation (so called mixed-mode) to achieve performance objectives cannot be simulated reliably without integrated air flow modelling. That applies especially where reliance on buoyancy forces, or on natural wind effects, is the design intent to achieve specific performance objectives. Certainly, extreme conditions such as warm weather overheating cannot be reliably predicted by simplified means. Building control strategies such as overnight free cooling depend on an accurate assessment of the energy flows into and out of thermal storage, with the ventilation air acting as a transport medium. More elaborate thermal storage mechanisms rely on accurate modelling in both the thermal and air flow domains. Active façade systems, where solar inputs, thermal transfers and air flow interact dynamically, are a particularly good example of the power of the integrated modelling approach.

Once established, a network flow model allows the appraisal of ventilation efficacy and controllability, the impact of infiltration on energy use, heat recovery potential, approaches to draught proofing, and the contribution of draughts to local thermal comfort.

Computational Fluid Dynamics

The air flow network method is a suitable approach where there is a strong coupling between thermal zones and the distributed air flow associated with building circulation pathways and HVAC plant: temperature and mass flow data can be readily passed between the two domains. On the other hand, the approach makes simplifying assumptions: that mass flow, including inherent turbulence effects, is a non-linear function of pressure difference only; the air within a zone is well mixed and may be characterised by a single temperature and pressure; and that the flows are realised instantaneously. Where such assumptions are unacceptable, a Computational Fluid Dynamics (CFD) model may be established. Now the air movement is determined as the solution of mass, energy and momentum balances at points within a discretised zone. Because the CFD domain is linked to the zone thermal and network air flow domain models, the CFD boundary conditions (temperature, mass and momentum inputs/ extracts) and source terms (heat, contaminants) can be varied throughout the simulation.

A typical application of the approach is to use one or more air flow network to represent the macroscopic aspects of overall building/ plant fluid flow and CFD to represent the microscopic aspects of air movement within zones of interest. Temperature or mass and heat flux boundary conditions can then be imported from the thermal simulation.

When setting up a CFD domain, a large amount of input data is required: mesh size and location, treatment of turbulence, near-wall conditions, convergence criteria, source terms and solver-related directives. Because a building may be characterised as an unsteady, low Reynolds Number flow problem, the parameters of the CFD domain must be redefined at each computational time-step based on an exchange of variables with other domains. The simplest approach is the one-way transfer of information from the thermal and air flow domains. For more realistic simulations the two-way transfer of information is required whereby thermal, air flow and CFD solvers search for mutually converged solutions. This is done by initialising each domain with information from the other and iterating until mutual convergence is achieved. Adaptive mechanisms are applied to readjust heat transfer coefficients, near-wall functions, mesh geometry, turbulence model parameters, buoyancy effects, and heat and mass sources based on the prevailing flow condition.

Once established, the CFD domain can provide an impressive level of detail on critical aspects such as temperature, humidity and contaminant distribution, local air movement (draught), the nature of flows (laminar, turbulent, buoyant), mean age of air and air quality, ventilation system effectiveness, cross-contamination potential, stratification and local comfort levels (to name but a few).

Lighting Simulation

The way buildings are used has a significant impact on the magnitude and distribution of internal heat gains, occupant perceptions of their environment as well as their productivity. Decisions about the provision and control of lighting is thus of considerable concern to design teams as well as code compliance regimes and points-based standards. As with other aspects of simulation, model planning and creation involves selection from several possible levels of resolution. The subsequent understanding of lighting performance is predicated on clear performance indicators which can vary depending on the stage of the design process and specific performance issue being addressed. Lighting functionality follows closely from the level of description.

At a low level of resolution only the heat generation properties of lighting are of interest and thus schedules of sensible gain magnitudes are required along with heat distribution fractions to zone air and surfaces via radiation. Control may be based on concepts of daylight factors or radiation levels at the facade. Where the design question is related to daylight utilisation as a means to displace electricity used for artificial lighting, the characteristics of photocell location and control logic must be defined in some detail. Where facades include controllable shading, the different possible states of the shading devices need to be described. A simple control actuator may be employed to alter the optical characteristics of the façade in response to some excitation. Where blinds are employed to re-direct radiation, bi-directional light transmission and absorption characteristics are required. Such data would be based on physical measurements or detailed ray-tracing computations.

Electrical Networks and Renewable Energy Systems

An electrical network may be established to represent alternating and/ or direct current systems, with time -varying, multi-phase, real and reactive power flows at multiple voltage levels. As with the network flow model, the electrical network is represented as a series of nodes and arcs, the former being points of interest, such as where power is withdrawn or supplied or where two conductors meet. The arcs are routes of electrical conduction and can represent electric cabling, power electronics (e.g. inverters) or transformers. The data structure for each node includes its voltage, real and reactive power supplied, real and reactive power drawn and real and reactive power transmitted to other nodes. The connector data structure typically only includes impedance data in the form of resistance and reactance.

The electrical network is integrated with the other domain models, using real and reactive power demands or supplies calculated in other technical subsystems of the integrated model, e.g. PV (renewable devices subsystem), lighting (internal schedules and control subsystems), CHP (plant subsystem). This information is used as the boundary condition for the solution of the electrical network, yielding voltage levels and internal and boundary power flows on a time step basis. As with the other domains within a high resolution model, the electrical network model can be developed to model power flows in more or less detail as follows.

At the simplest level, the network can be used to record electrical real and reactive power supply and demand, including import and export from the grid and supply from connected low carbon technologies. This requires the definition of a single fixed voltage node and the connection of entities such as lighting loads, PV or CHP generation to it.
Adding a single-phase electrical network topology allows the model to actively track real and reactive power flows within the building's distribution system and also to calculate voltages at critical points. This allows the identification of phenomena such as cable losses, possible overloading and low and high voltage levels. Such a network requires the definition of an electrical network topology (i.e. multiple nodes and their connectivity), the provision of live and neutral conductor impedance data and the connection of power consuming or generating devices as active elsewhere in the model.

Finally, a fully elaborated (and realistic) three phase network topology can be developed. This requires all of the information outlined above, along with details on the mutual magnetic and electrical couplings between conductors occupying the different phases in an electrical component such as a cable or transformer; these are defined in terms of coupling impedances and would typically be derived from a test on electrical equipment. A full three-phase model allows the electrical network to track real and reactive power flows, power factors, and voltages through the individual phases of a typical power distribution system such as that found in large buildings or serving communities. This enables the identification of power quality problems such as current and voltage imbalances in conductors and devices.

Conclusions

Integrated simulation applied to a high resolution model of a dwelling permits a realistic and rigorous appraisal of performance and, in the context of refurbishment, a confirmation of effectiveness prior to deployment. The construction of such a model requires collation of information from different sources and this paper has identified these data and sources.

Table 2: ESP-r technical aspect data models.

<u>Network Fluid Flow</u>

- Fluid type (air, water *etc.*).
- For each network node:
  - internal nodes:
    - user-specified pressure and/or temperature;
    - location of equivalent node within zone energy balance domain (to allow imposition of temperature prior to solution for pressure)
  - external nodes:
    - user-specified pressure and/or temperature;
    - related surface azimuth;
    - height above datum;
    - related pressure coefficient set (temperature assigned to prevailing external air temperature, pressure established from pressure coefficient based on wind velocity adjusted for height).
- For each flow component:
  - type (pump, fan, restrictor, tee, crack, doorway, opening *etc.*); automatically establishes an empirical mass flow model;
  - model parameters (areas, diameters, equation coefficients/exponents *etc.*).
- For each inter-nodal connection:
  - node on 'positive' side (arbitrary designation) of connection;
  - node on 'negative' side of connection;
  - height of connection link relative to positive side node;
  - height of connection link relative to negative side node;
  - list of linked components (e.g. vent, door, fan *etc.*).
- Solver parameters:
  - type (Newton-Raphson, Gauss Siedel);
  - maximum number of iterations;
  - largest allowable cell residual;
  - pressure correction relaxation factor.

<u>Computational Fluid Dynamics</u>

- Number of grid lines along x-, y- and z-axes and power law coefficients to dictate mesh reduction at near-surface locations.
- Activation of optional equations for solution (buoyancy, contaminant concentration).
- For each boundary opening:
  - type (pressure, mass/volume flow, zero velocity gradient *etc.*);
  - location (East, West, North, South, High, Low);
  - initial and final cells in x-, y- and z-direction.
- For each solid boundary:
  - type (temperature, heat flux, symmetry plane);
  - location (East, West, North, South, High, Low);
  - initial and final cell in x-, y- and z-direction.
- For each heat/contaminant source:
  - type (heat flux, contaminant flux);
  - initial and final cell in x-, y- and z-direction;
  - blocked cells identification.

- Solver parameters:
  - initialisation of cell pressure, temperature and flow rates based on previous time step values;
  - maximum number of iterations;
  - number of solution sweeps;
  - largest allowable cell residual;
  - relaxation factors per parameter.
- Coupling and adaptive adjustments:
  - temperature and air flow coupling to thermal and air flow domains to vary boundary conditions;
  - models for alternative near-wall treatment for non-turbulent flows anticipated on the basis of an exploratory simulation at the start of each time-step.

Lighting simulation

- Full geometrical description (with higher resolution at the façade than for thermal models).
- Geometry and location of zone furniture and fittings.
- Surface optical properties for opaque elements.
- Optical transmission properties for transparent elements.
- Optical properties and control states for blinds.
- Switching characteristics of electro-, thermo- or photo-chromic glazing.
- Position, viewing direction and response characteristics of photocells.
- Position and distribution characteristics of luminaires, use schedules if control not automatic.
- Sky luminance distribution.
- Ground topography and reflectance.
- Geometry and surface properties of adjacent buildings and natural features.

Electrical network and renewable energy systems

- For the whole network:
  - description;
  - type (a.c., d.c., single-phase, multi-phase, mix of previous).
- For each network node:
  - description;
  - type (variable voltage, fixed voltage);
  - current (a.c., d.c.);
  - single-phase or multi-phase.
- For each electrical load:
  - description;
  - type (lighting, fan, pump *etc*.);
  - building location (zone, plant component *etc*.);
  - load model;
  - model data (position, associated building component *etc*.).
- For each generator:
  - description;
  - type (PV, CHP *etc*.);
  - building location (façade-integrated, roof mounted, free standing, associated with an HVAC component *etc*.);

  - generator model;
  - model data (position, associated plant component *etc*.).
- For each connector component:
  - description;
  - type (cable, transformer *etc*.);
  - start and end node (or nodes if multi-phase);
  - phase and neutral conductor impedance data;
  - mutual impedances between conductors;
  - connector model;
  - model data.
- Solver parameters:
  - type (Newton-Raphson, Gauss Siedel etc.);
  - voltage convergence criteria;
  - apparent power flow convergence criteria;
  - maximum voltage change/iteration.