A DATA MODEL FOR INTEGRATED BUILDING PERFORMANCE SIMULATION

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ABSTRACT

Integrated building performance simulation (IBPS) can improve building design by allowing comprehensive appraisals under realistic operating conditions. However, the complexity of the problem domain can render the approach difficult to apply in practice due to theoretical limitations, component data paucity, *ad hoc* approaches to performance assessment and partial problem coverage. By presenting the data requirements of several significant technical domains addressed by the ESP-r system, this paper addresses the last issue. Inclusion of such comprehensive data structures would augment the geometric focus of current Building Information Models (BIM) and thereby support integrated performance appraisal.

IBPS OVERVIEW

There exist many tools for the prediction of aspects of building performance (US DOE 2011) but relatively few that offer an integrated approach whereby all aspects of performance can be addressed simultaneously. The ESP-r (2011) system is such a tool (this statement should not be taken to imply that this tool or the IBPS approach in general is easy to apply in practice).

Consider Table 1, which summarises progressive stages of building data model evolution within ESP-r and the corresponding performance assessments enabled at each stage.

An initial, modest effort on the part of a user – say examining a pre-constructed database of material properties or a library of past projects – can yield a significant reward, such as the sourcing of a material with low embodied energy, useful moisture absorption, rapid response to a temperature fluctuation, high thermal storage potential, resistance to vapour flow *etc.* 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.

Table 1: input/output associations within ESP-r.

CUMULATIVE PROBLEM DESCRIPTION	PERFORMANCE ASSESSMENT ENABLED
pre-existing databases	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 glazings
+ 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

It is at this point that conventional modelling is left behind and the emerging potential of IBPS 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 (i.e. the data model extended) to allow an assessment of comfort and air quality under the influence of realistic boundary conditions and sources/sinks of heat, moisture and contaminants.

From a modelling viewpoint, the integrated approach requires the simultaneous solution of equation-sets representing the processes occurring within each technical domain (building-side heat flow, inter-space air flow, intra-space air movement, constructional moisture flow, plant-side energy flow, electrical power flow, light flow and control signal flow). Within ESP-r this is achieved by invoking solvers that are tailored to individual domain equation-sets, as and when the related data model becomes available, and placing active solvers under global iteration control to ensure that appropriate interface variables are exchanged at the required frequency (Clarke 2001).

From a user's viewpoint, a significant effort is required to progressively populate the data model if the ultimate aim is to address the challenges of sustainable energy utilisation without loss of user amenity and the realisation of environmental conditions conducive to occupant well-being. What good is a home energy efficiency measure if it adversely affects indoor air quality, or a local micro-generator that reduces global emissions but pollutes the occupant's breathing zone?

In use, the IBPS approach facilitates an integrated performance appraisal of problems of arbitrary complexity and scale. For example, a model might be established to allow an appraisal of energy efficiency measures and local supply solutions as a way to meet net zero carbon building standards. With some refinement to the data model it would then be possible to ensure that such standards were not being attained at the expense of human health or that the adapted loads improved the match with the power profiles available from local, small scale renewable energy systems.

BIM OVERVIEW

Significant effort is being expended to create a building data model that supports information exchange between CAD systems and various performance-related applications. Presently, these efforts are focussed on IFC (buildingSMART 2012) and gbXML (2012) schemas. While these efforts are making progress, significant gaps remain in rwlation to an integrated data model as eluded to above. The gbXML schema, for example, presently comprises 115 *SimpleTypes* and 260 *ComplexTypes*. However, many of these entities are empty containers that need to be evolved if the needs of IBPS are to be served – the same is true of the IFC schema (O'Donnell et al 2011). For example, the gbXML *equipmentTypeEnum* offers 19 choices while *systemTypeEnum* offers 49 choices but all are shallow lists with only a name and a brief description but no describing data. The *AirLoopEquipment* and *HydronicLoopEquipment* types have a number of general attributes but lack the specific data definitions that could be used to encapsulate actual representations within IBPS. Many domains – renewable energy systems, low voltage electrical networks, constructional moisture flow and air flow/movement are not addressed at all. Likewise, the performance side is superficially represented: the *resultsTypeEnum* includes 21 items, some of which are dimensional wrappers (e.g. *FootCandles*) and some lack specificity (e.g. *DemandCost*, *Flow*). Concepts such as glare, local draught, contaminant concentration, condensation, thermal comfort, indoor air quality, power factor, emissions and so on are absent, as is component-oriented performance making it impossible to address issues such as evaporator defrosting, flue gas heat recovery, boiler firing rates and damper control response. Further, the constituents of energy and mass balances, which are often employed to investigate the cause of poor performance, are missing.

TECHNICAL DOMAINS IN BIM

Although BIM currently focuses mainly on geometrical aspects of the building design, future developments must extend the description to cover all technical domains and performance. These data are already available within IBPS and the following section presents principal domain examples as defined within ESP-r.

While the ESP-r integrated data model covers all aspects of building representation – from geometry & construction & operation, through HVAC & control, to new & renewable energy systems – only a portion is discussed here because of the space restriction. These correspond to network air flow, computational fluid dynamics, lighting simulation and electrical networks incorporating renewable energy systems. Likewise, the cited performance appraisal capabilities related to these domains are but a subset of what is possible in practice.

ESP-r INTEGRATED DATA MODEL

Table 2 lists the specific data requirements of 4 ESP-r technical domains, which are considered here because they are likely to add significant value to any existing BIM schema in terms of the new appraisal functionality then enabled.

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. Air within a building is often treated as a non-dynamic element, with losses specified in terms of fixed air change rates or, at best, inter-zone exchanges. 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 likely result in many cases is a significant 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:

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.
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 (Figure 1), 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.

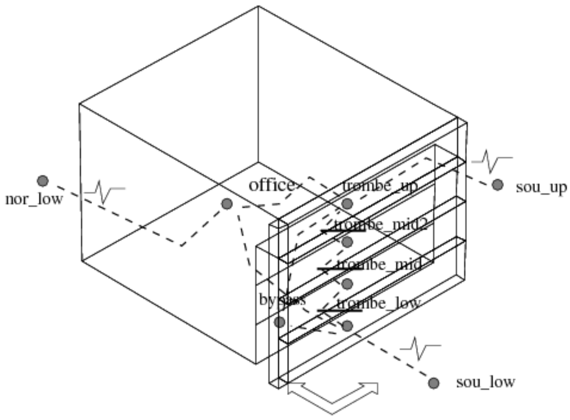

Figure 1: a conflated thermal air flow model.

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 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 & 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 & 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 relating to describe the problem being addressed and parameters that control the solution: 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 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 also available. These 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. For cases with convergence problems coupling parameters can be adjusted to aid convergence. Once convergence is reached for this reduced data setup a full CFD run is initiated with the domain initialised in an informed manner.

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 such as LEED. 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. Ideally such data would be based on physical measurements or detailed ray-tracing computations.

Much research has focused on occupant control of lighting and blinds. In real buildings, occupants move around and have different perceptions and likely responses to perceived changes in their visual field. In this case, the data model needs to hold information about temporal movement and the range of preferences.

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. In multi-phase mode, each phase of the network is fully elaborated using a similar approach to that outlined by Kersting (2002) among others. 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 ESP-r, 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 other ESP-r 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 ESP-r 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.

The ESP-r electrical model can be interrogated at different levels with many of the quantities mentioned above aggregated for the entire network (e.g. total renewable electricity contribution) or reported at the level of individual components.

DATA REPRESENTATION

The first step in developing interoperable and/or integrated design tools is to identify the input data requirements and the performance outputs for the various domains as described above. The second step is to develop a structure for describing the relationships between the data – the data types, the links between types, constraints on relationships, validation checks *etc*. This requires a data model schema.

An early example of a schema for building performance modelling was the one established within the COMBINE project (Augenbroe 1995, Clarke *et al* 1998). Graphical entity-relationship modelling was used to describe the relationships between the data inputs for building context & fabric, air flow networks and system control. This used ATLIAM representation, an extension of the Natural Language Information Analysis Method (NIAM); the graphical data could then be parsed into the EXPRESS language (Spiby 1991). An example ATLIAM diagram describing the data representation of ESP-r's network flow model is given in Figure 2. Some elements in the diagram, for example *flow_node*, are further decomposed in other linked diagrams. Translators were developed to map the EXPRESS format into ESP-r input files and *vice versa*. These translators need to be sophisticated enough to apply constraints such as limits to the range of validity.

The advantage of using a schema representation model such as NIAM is that it provides a conceptual framework for describing the data model and allows related items to be stored and accessed in an effective way. A more up-to-date variation of NIAM is the Natural Object Role Modelling Architect for Visual Studio (NORMA 2012), which is an Open Source plug-in to Microsoft Visual Studio. With this it is possible to transform a NIAM schema to an XML schema.

CONCLUSIONS

A fully populated data schema is a requirement for IBPS in BIM. This paper has presented some examples of the detailed data required, with the inference that the schema definition should be informed by domain specialists (and by developers of different programs to ensure completeness). A successful outcome will operate in synergy with broader multi-domain BIM schema such as IFC and gbXML. It is recognised that the development of comprehensive schema will be large and complex, and in practice it will be necessary to move towards the goal incrementally.

The extraction and reorganisation of ESP-r's data model is being undertaken within a project which is attempting to extend the scope of CAD by the addition of new dialogues covering non-traditional topics such as HVAC, CFD and control systems, while automating the initiation of simulation tasks and the display of performance returns through summary, statistical, spatial and temporal data.

The contention is that BIM must be informed by, and support the application specific requirements of, IBPS and that the data schemas should incorporate entity-relationship structures to maximise efficiencies.

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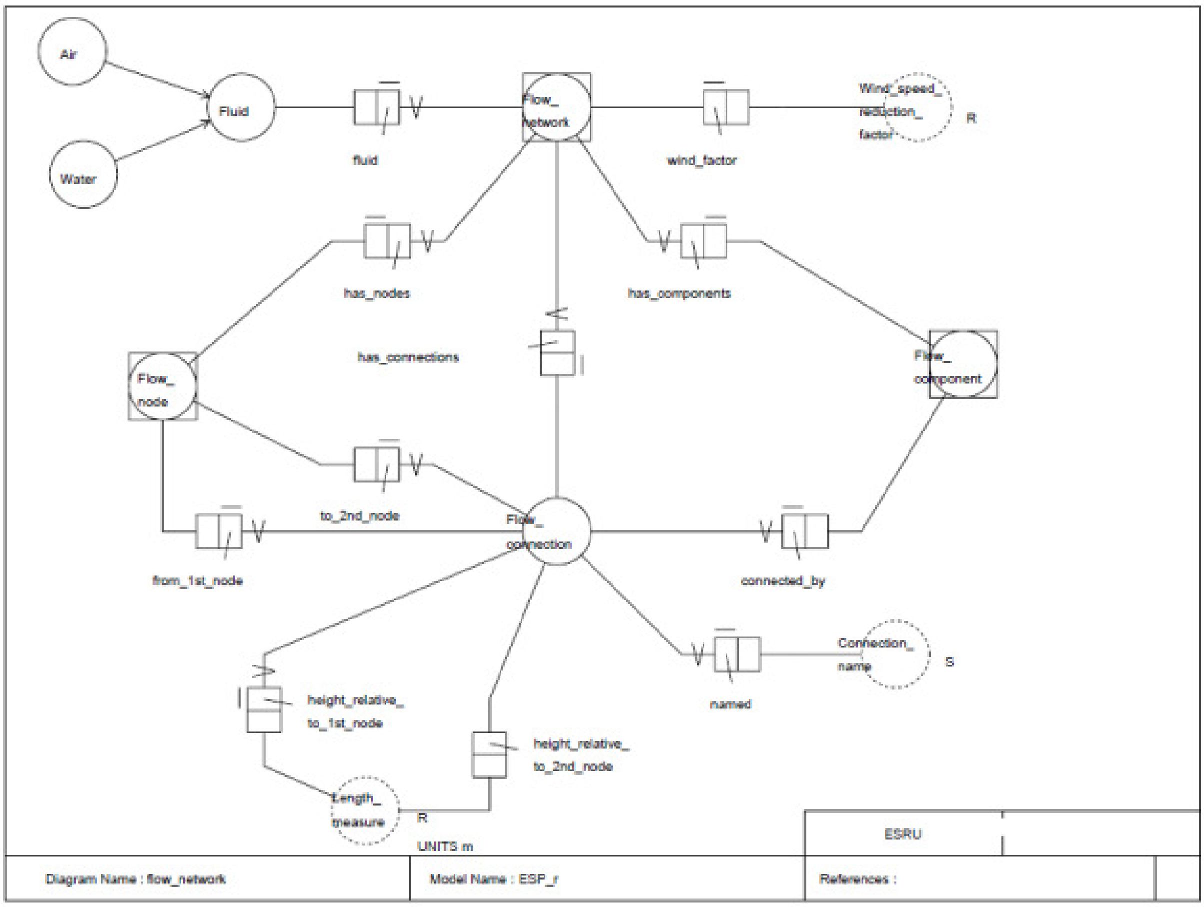

Figure 2: Example ATLIAM diagram for an ESP-r fluid flow network.

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 or
    - 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 or:
    - 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-nodel 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

<u>*Lighting simulation*</u>

- 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)
  - voltage convergence criteria
  - apparent power flow convergence criteria
  - maximum voltage change/iteration