ABSTRACT
Many simulation teams create models of empty buildings e.g. without furnishings and fittings. This paper explores what happens if sunlight actually falls on desks and chairs and filing cabinets rather than the floor as well as what happens if interior artefacts were treated with the same rigour as facades by the simulation engine.

Typically increasing model resolution is a tedious process and added detail if included, may not be fully utilised. To explore removing such barriers, a data store of pre-defined entities, which include provenance, visual form, explicit thermophysical composition, light distributions and mass flow attributes has been introduced in ESP-r. ESP-r facilities for calculating view-factors and insolation distributions have been updated to include this extended data model. Issues related to creating and managing such entities is discussed and the impacts of their use is quantified via case studies.

INTRODUCTION
The physics that apply to building facades and within rooms also apply at the scale of the thermo-physical clutter that surrounds us. All have measurable form and composition and interact with their surroundings in ways that are often neglected in traditional approaches. Simulation tools include provisions for abstract as well as more explicit representations of building entities (Crawley D. Hand J 2008) and the level of abstraction is, to some degree controlled by the practitioner. Certainly there are practitioners who believe that thermophysical clutter has a minimal impact on the assessments they undertake and not worth being literal about.

But business is not done in empty office buildings (Figure 1) and simulations of unreal situations can have impacts on evaluating temporal perceptions of comfort as well as response characteristics of environmental controls. The impact of different levels of abstraction is worthy of testing and this paper explores whether excluding or including what might be termed ‘thermophysical clutter’ either abstractly or explicitly matters. It asks whether there is new information to be gained from designing models which are less abstract and solving a more comprehensive virtual world?

Recent work with ESP-r has introduced pre-defined entities that go beyond normal practice to include visual form and light distribution characteristics to pass to Radiance, explicit surfaces to represent mass and network flow attributes for the zone and flow solvers. One class of pre-defined entity is designed for inclusion in an existing thermal zone (e.g. office chairs, bookcases, light fittings), a second class includes complex building and façade assemblies (stairs, glazing/frame combinations). A third class includes system components, such as zonal representations of thermostats, radiators, and accumulators.

If an office has two desks three chairs, two monitors, a suspended LED fitting and a filing cabinet a practitioner could manually approximate the composition and surface area for these objects, but this is both tedious and subject to error. The goal of the facility is that the selection and placement of such objects imports sufficient attributes for full participation in both visual and thermophysical assessments. Once embedded in zones they fully participate in the zone, flow and visual solvers. If creating a literal distribution of desks requires little additional attention on the part of the user and does not have a marked impact on the speed of solution the need for abstraction may be reduced.

Simulation tools ability to accept representations of internal artefacts is only a first step. Facilities for coupling them into numerical assessments vary considerably. Do the methods for assessing insolation

Figure 1: What our models tend to represent
distribution, long wave radiant exchanges and surface convective transfers treat these artefacts at the same or a different level of rigour as other building entities?

The paper reviews the underlying data model and its evolution as new types of entities have been included. It will also explore the implications of including furniture and fittings at several levels of abstraction in a residence and office. The impact on occupant perceptions of comfort, control performance differences will be explored as well as the resources needed for model creation, simulation and data recovery.

**JUSTIFICATION**

Abstract representations of internal thermal mass as surface area and composition entities have been widely available in simulation tools. (Waddell and Kaserekar 2010). The EnergyPlus Engineering Reference (DoE 2016) reflects a common consensus of many vendors and practitioners: "Furniture in a zone has the effect of increasing the amount of surface area that can participate in the radiation and convection heat exchanges. It also adds participating thermal mass to the zone. These two changes both affect the response to temperature changes in the zone and also affect the heat extraction characteristics. The proper modeling of furniture is an area that needs further research...".

Longwave radiation transfer in many simulation tools is also problematic for the treatment of furniture and fittings. The EnergyPlus (DoE 2016) approach is, again, typical: "EnergyPlus uses a grey interchange model for the longwave radiation among zone surfaces (Hottel and Sarofim 1967). This procedure relies on a matrix of exchange coefficients between pairs of surfaces... In the case of building rooms and zones, there are several complicating factors in finding the direct view factors—the main one being that the location of surfaces such as thermal mass representing furniture and partitions are not known. The other limitation is that the exact calculation of direct view factors is computationally very intensive even if the positions of all surfaces are known. Accordingly, EnergyPlus uses a procedure to approximate the direct view factors."

In some tools users can over-ride such approximations and the sequence for EnergyPlus is described in (Bigladder 2016) where the authors note "EnergyPlus has the capability of accepting user defined view factors for special research situations. This option is not recommended for general use..."

ESP-r also uses a grey interchange model and viewfactors. However, the limitations mentioned above have been addressed. Exact calculation of direct view factors for zones and surfaces of arbitrary complexity are supported and the position of all bounding and internal mass surfaces are known. The computational burden at the limits of zone complexity within ESP-r is in the order of seconds.

Our models routinely track the influence of facades but desks near facades often act like inefficient solar collectors which dump heat into the room air and onto nearby occupants. Being close to warm or cold surfaces is a classic source of discomfort and some practitioners are adept at checking divergence of dry bulb and MRT but we really need metrics such as radiant asymmetry at position specific MRT to track local discomfort.

Some comfort tools exist (ASHRAE 2011) that report average MRT and comfort. Detecting local discomfort via MRT might be clearer if the model geometric resolution is increased and if position-specific MRT and comfort metrics are used. A recent ASHRAE project RP 1383 (ASHRAE 2015) resulted in a tool kit for predicting position-specific comfort. ESP-r has had such facilities for a decade so we can use this to explore how the inclusion of predefined objects might impact the detection of local discomfort.

**APPROACH**

ESP-r simulation tool (Hand 2015) has been used as a test bed for a number of reasons:

- It is open source and can be adapted to support this study
- Its data model already includes entities for explicit thermal mass and visual entities.
- It supports calculated view-factors between surfaces in rooms of arbitrary complexity.
- It supports local comfort assessments with radiant sensor bodies within rooms.
- It supports insolation calculations in rooms of arbitrary complexity.
- It supports exports to Radiance and would only require incremental changes.

Indeed, researchers and practitioners using ESP-r have been inserting mass surface pairs within zones for more than a decade. The drawback – these are ad-hoc creations without a concept that a cluster of entities constitute an object.

The goal of pre-defined entities is to provide access to a diverse collection of objects that commonly populate buildings and support their insertion into the simulation model without specialist skills or the need for pedantic working practices. They should be visible within the model and part of the model contents reports to ensure clarity and reduce errors. Each entity would include sufficient attribution to support multi-domain assessments with little or no additional interaction from the user (beyond selection and placement directives). They should have a clear provenance, documentation as to their intended use as well as subsequent actions required by the user. Each would include directives to be interpreted by
the simulation tool to ensure dependencies are resolved as well as user directives.

**IMPLEMENTATION**

Pre-defined entities have been implemented as a database within the ESP-r suite. The data structure of a pre-defined entity is a subset of that used by ESP-r for thermal zones and surfaces. In some cases new concepts required extending the zone data structure. Each pre-defined entity includes the following:

- **Header:** object name, a menu entry, documentation text, provenance, geometric origin and bounding box (for preview) and merge-into-model directives.
- **List of vertices**
- **Mass surface pairs (name, composition, optics, usage, ordered list of edges)**
- **Boundary surfaces (name, composition, optics, usage, ordered list of edges)**
- **Visuals (name, composition, type, origin, rotations, bounds/list of vertices)**
- **Solar obstructions (name, composition, type, origin, rotations, bounds/list of vertices)**

Selection and management follows the same pattern as other ESP-r databases (point to a common or model specific database), the drill down through categories to preview or use an object. The author would, of course, need to ensure it is a reasonable abstraction using the available primitives and attributes.

For example a computer monitor is a mix of visual shapes and thermal entities representing the case of the monitor as well as the electronics it contains. Its documentation provides the provenance as well as its electrical characteristics.

Populating the database requires gathering dimensional and composition attributes via tape measure, callipers and digital scales. Establishing typical weights of a bookcase or filing cabinet is straightforward if somewhat tedious. Sometimes disassembly is necessary. Some examples from the initial database:

- **Office furniture:** standard swivel office chair, wood office desk 0.6mx2.0m, office desk 0.6mx1.6m, four drawer file cabinet, double four drawer file cabinet, 55cm diag wide screen dell monitor...
- **House furniture:** TV 53cm wide, coffee table 0.50x1.05x0.32m, Ikea book case 0.38x0.28x2.02m, Ikea book case 0.80x0.28x2.02m, double bed with solid head & foot, wooden chair with arms, arm chair with fabric cover...
- **Zonal environmental system components:** standard honeywell CM707 thermostat, radiator 1.1x0.5m one zone water filled, radiator 0.6x0.5m one zone water filled...
- **Facade components:** PVC_1.8 framed window 1.8mx1.2m, upvcPH18x12 PH-ish UPVC window, five section residential bay window...
- **Lighting fixtures:** suspended 1.25x0.15m LED fixture, thorlux 600x600x10mm...

Once selected those viewing the model get visual clues and model QA is enhanced because standard entities have been used rather than ad-hoc creations.

Figure 2 shows an office chair. The mass of the seat and the back are represented but the mass of the legs and the arm-rests have been omitted. Overheating from sun falling on the seat and back is intended to be indicative.

Some elements of buildings such as stairs and façade assemblies are ubiquitous and geometrically complex to the point of being ignored or highly abstracted. The challenge of hosting such complex objects and allowing them to be merged into a model did much to generalise the data structures.

The extended data structure allows us to consider alternative to the usual-suspects for other domains. What happens if users swap abstract control sensors directives with a predefined control sensors that uses the radiant, convective and mass flow solvers? In Figure 3, the components in a Honeywell thermostat have been explicitly represented. The bounding surfaces of the case become surfaces in the zone and fully coupled to it. The control logic points to the sub-surface sensor state rather than the usual algorithm.
RESIDENTIAL EXAMPLE

Figure 4 shows a model of a typical 88m$^2$ semi-detached UK house circa 1955 (there are tens of thousands of these in the UK). A standard ESP-r model where each room plus the crawl space, attic and equipment space under the stairs are treated as separate thermal zones. The stair was manually created but otherwise there are no exceptional features in the model and it would be fit for a wide range of studies.

In support for an IBPSA conference paper (Clarke et al. 2015) looking at the impacts of more explicit building descriptions the residence was manually upgraded to include some of the furnishings as well as explicit (zonal) representations of the radiators, boiler, solar collector and accumulator (Figure 5). The solution then uses the zones and flow network to explicitly solve a wet central heating scheme with solar backup. We also tested a CFD representation of the boiler combustion chamber.

These add visual scale to the model and assisted in damping of some temperature fluctuations. But the furnishings were crude representations despite the time taken and much was omitted.

Once the new facility was implemented the initial model of the house was populated with a range of furnishings and fittings and the stair replaced with a pre-defined unit. As the user-burden was reduced it was possible to include bookshelves, chairs and a television with less time than had been required for the initial manual furnishings (Figure 6).

Conceptually the kitchen cabinets, bay windows, solar collectors, accumulator and other system components could be hosted as pre-defined objects but this has not been done in the current study.
VISUAL ASSESSMENTS

ESP-r has long had a Radiance export facility. One of the work-flow complications of doing mixed thermal and visual assessments is the need to edit Radiance files. Although we claim that simulation is a super-set model there are gaps. Pre-defined entities fill in one of these gaps with objects designed for multi-domain assessments. With the fully populated residence model a glare assessment is straightforward (Figure 7).

Working with models including artificial lighting was always implied many iterations of edit and test. With a pre-defined lighting objects users need only copy the fixtures IESNA file into the model rad folder. Once in place the fixture can be induced to change its lighting state during the simulation so that both natural and artificial lighting can be sensed for control purposes.

SOLVERS

One goal of the study is to make full use of the predefined entity attribution. After inclusion in the model, the thermophysical portion of a predefined object are treated no differently than any other surface in the model within the solution process. ESP-r detects the change in complexity and offers to recalculated viewfactors as well as updating shading/insolation patterns.

ESP-r’s insolation calculation bookkeeping has been adapted to more robustly identify when internal surfaces occlude room boundary surfaces and to display insolation calculations as they are computed. Figure 8 shows grids of insolation points (blue dots) on the desk, adjacent wall and floor from a source window (red dots)) during an isolation calculation. Insolation calculations and view-factors require a few additional seconds to calculate in comparison with an empty model.

OFFICE EXAMPLE

A second example is a portion of an office block in Ottawa which initially included a somewhat abstract representation of desks near the perimeter of the rooms and a large table in conference room (Figure 9). The intent was both to improve the clients understanding of the model as well as account for some of the thermal impacts of internal mass.

It preserves overall surface area, mass and placement of the desks but results in a single temperature at the upper face and lower face of the desk in each room. It took roughly 15 minutes to implement this in the original model.

Model variants also include an empty building and one populated for an office usage case (Figure 10). The assessment includes explicit surface-to-surface viewfactors, MRT sensor bodies as well as an insolation analysis. The initial model includes 125 surfaces and the model with predefined entities
includes 311 surfaces and 446 visual blocks. The largest room went from 35 to 93 surfaces as a result. What does this cost in terms of computing resources? A 93 day assessment at a 15 minute time-step for the initial and pre-defined variants required 10s and 1m33s on a Dell 780 computer. An annual run on a Lenovo X220 laptop took ~25 seconds for the model with abstract desks and ~4m for the populated model. Using the maximum level of performance data storage the zone results files were 224 & 1200MB respectively and with a moderate level of performance data saved an annual assessment requires 40 & 343MB. Extracting data for a standard performance report task took less than 10 seconds in all cases. Radiance images of the abstract desk view comprised 45 million rays took 5m1s (Figure 15) and the view with pre-defined objects was 70 million rays and 9m1s (Figure 16).

Is this a sufficient computational burden to preclude the use of less abstract models? Certainly there are many work-flow and hardware choices that would mitigate much of this overhead. Is is useful to spend an additional minute or two when creating the zone in terms of new performance information?

If we turn to the surface temperatures for the floor, glazing, desks and storage in Figure 13 the empty floor is up to 1.2C warmer than in the populated model while the floor in the abstract model is in the order of 0.5C. The abstract desk peaks at ~31C while the more explicit desks peaks at ~29C and ~33C. The caper surface is the storage and is dampened in comparison with the other room surfaces as expected. The diversity of internal mass tends to have many lightweight furniture elements and one storage mass. Thus the inertia of the room is not greatly shifted even though there are now extreme temperatures introduced.

Focusing on the cellular office (active room surfaces shown in Figure 11) - the room drybulb, resultant and average MRT temperatures are shown in Figure 12. The first day is free floating and all temperatures are within ~2C. On the weekdays the dry bulb temperature is controlled to 24C during office hours an the elevation of resultant temperature is ~2C and MRT is ~5C. The range between the MRT in the model variants is in the order of 0.7C with the empty room being the warmest. Control on air temperature (which real thermostats do not measure) in a simulation model would seem to ignore risk of discomfort to occupants. Over the year the populated model had slightly lowered resultant temperatures.

**Figure 10:** Updated model with pre-defined objects.

**Figure 11:** Manager surfaces participating.

**Figure 12:** Manager variant temperatures.
While the abstract desk is energetically correct the use of explicit desks provides additional information on the temporal characteristics and spatial risks. For rooms with much more paper storage than is included in this model we find that the inertia of the rooms begins to alter the patterns of heating and cooling demands. This would also be expected for abstract descriptions of thermal mass.

The diversity of mass types in furniture and fittings seen in this study suggests that abstract representations should also be subdivided into a diversity of mass types rather than averaged mass.

The elevated desk temperatures would, of course not be identified in abstract representations that have no position. This would seem to introduce some risk into assessments for buildings which have furniture near facades. Not only are potential discomfort metrics missing (such as PMV in Figure 14) the distribution of heat gains within the rooms is not tracked.

On the last day of the assessment the peak solar on the floor is 41.2W/m² in the empty room, 21.4W/m² in the abstract desk room and 19.8W/m² in the populated room. The aggregate solar on the floor that day is 3.44kWhrs, 1.94kWhrs and 1.64kWhrs respectively.

In terms of heating and cooling capacity there are minimal differences between the office model variants. Annual heating and cooling demands are within a few 100kWhrs but there are hundreds of hours where heating and cooling demands are shifted or eliminated in the fully populated model. Exploring such temporal variance is beyond the scope of this conference paper but would be of interest to control engineers.

CONCLUSION

This paper provides an overview of a facility for hosting common objects with attributions supporting multi-domain assessments and increased model resolution. A residence and office have been presented with different levels of resolution. Observations from the use of the pre-defined object store as opposed to empty rooms and ad-hoc manual insertion of internal details indicate a savings in time, greater diversity in internal mass types and, importantly, less chance of model error.

The change in simulation work-flow provided by this ready access to objects was seen to remove barriers to the creation of higher resolution models. Especially in the case of joint thermal and lighting assessments the reduction in the need to edit Radiance model files provides scope for enhanced modelling deliverables with lower resource requirements.

Images often are more easily interpreted than phrases in reports (this as much as the thermal impact was important in the original office model). Ad-hoc additions such as columns in rooms are often a pragmatic approach. The magnitude speed up in populating models for clarity is for some a valid use of the facility.

The ability to track variability in surface temperatures and MRT within rooms and the increased diversity from identifying local discomfort is a useful option in some simulation studies. Simulation work flows and planning activities will need to change to identify the degree to which additional resolution is useful and whether relevant common entities exist for use or adaptation.
processing view factors and insolation patterns has been seen to impose only a minor computational burden.

In the case of the office, there was a ~3 minute computationally time penalty for the fully populated model during an annual assessment at a 15 minute time step against the empty model on a five year old desktop. Increasing model complexity results in larger results files and has minor impacts on data mining tasks. User appreciation of new metrics such as local comfort may require some re-training.

Initial indications are that the use of the facility to populate models has minor impacts on peak and overall heating and cooling demands. We observe that the distribution of heat gains within rooms changes as they are populated. Lightweight components close to facades alter the response characteristics of the room just as the inertia of filing cabinets dampens changes. These temporal patterns of environmental control actions may be of interest to control engineers and for assessments where local comfort is an issue.

Figure 15: Radiance view of abstract office.

Figure 16: Radiance view of populated office.

REFERENCES


