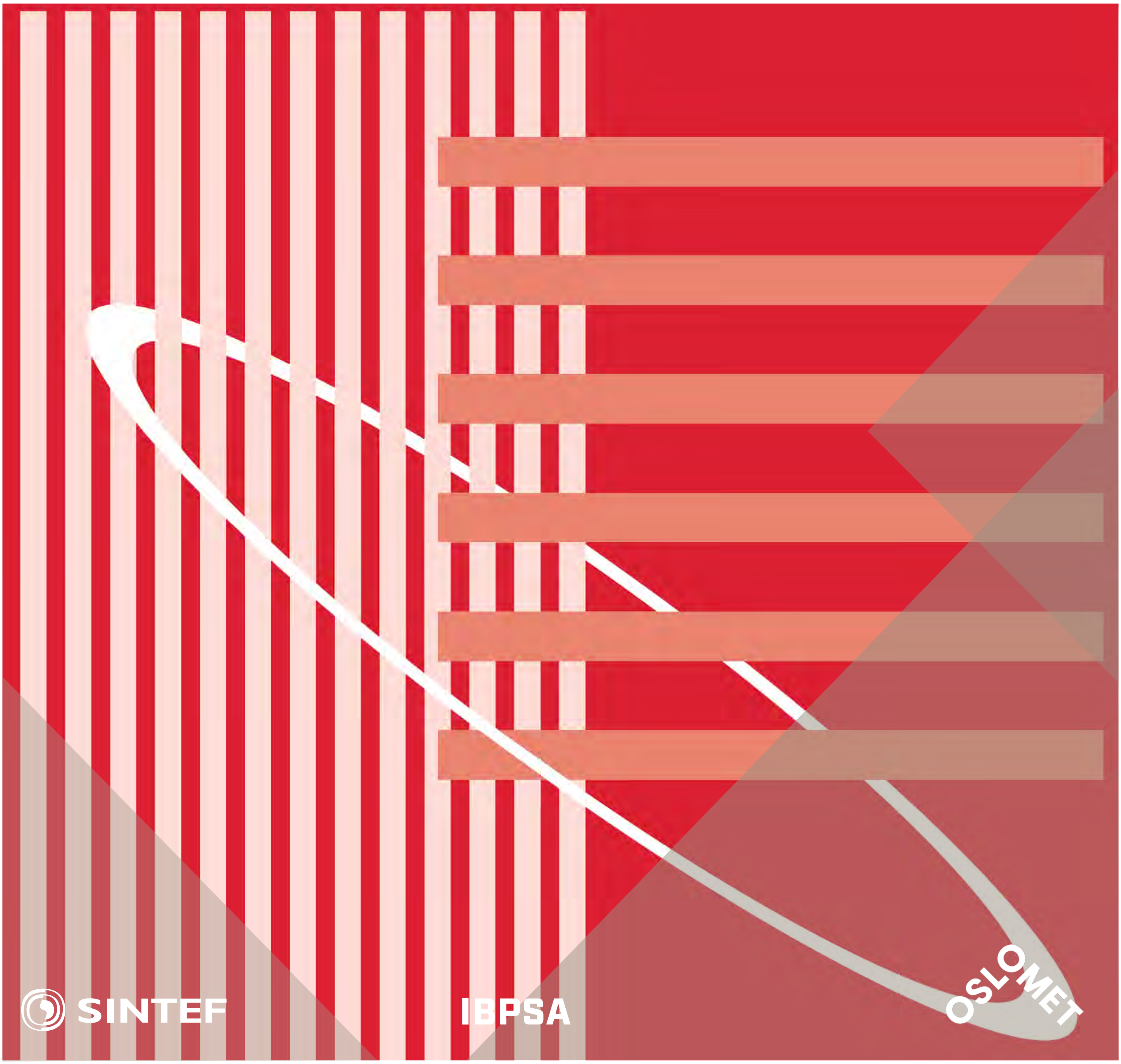
SINTEF
PROCEEDINGS
5

International Conference Organised by
IBPSA-Nordic, 13th–14th October 2020,
OsloMet

BuildSIM-Nordic 2020

Selected papers



SINTEF Proceedings

Editors:
Laurent Georges, Matthias Haase, Vojislav Novakovic and Peter G. Schild

BuildSIM-Nordic 2020

Selected papers

International Conference Organised by IBPSA-Nordic,
13th–14th October 2020, OsloMet

SINTEF Academic Press

SINTEF Proceedings no 5
Editors:
Laurent Georges, Matthias Haase, Vojislav Novakovic and Peter G. Schild
BuildSIM-Nordic 2020
Selected papers
International Conference Organised by IBPSA-Nordic,
13th–14th October 2020, OsloMet

Keywords:
Building acoustics, Building Information Modelling (BIM), Building physics, CFD and air flow, Commissioning and control, Daylighting and lighting, Developments in simulation, Education in building performance simulation, Energy storage, Heating, Ventilation and Air Conditioning (HVAC), Human behavior in simulation, Indoor Environmental Quality (IEQ), New software developments, Optimization, Simulation at urban scale, Simulation to support regulations, Simulation vs reality, Solar energy systems, Validation, calibration and uncertainty, Weather data & Climate adaptation, Fenestration (windows & shading), Zero Energy Buildings (ZEB), Emissions and Life Cycle Analysis

Cover illustration: IBPSA-logo

ISSN 2387-4295 (online)
ISBN 978-82-536-1679-7 (pdf)

Published by SINTEF Academic Press 2020

SINTEF Academic Press
Address: Børrestuveien 3
PO Box 124 Blindern
N-0314 OSLO
Tel: +47 40 00 51 00

www.sintef.no/community
www.sintefbok.no

SINTEF Proceedings
SINTEF Proceedings is a serial publication for peer-reviewed conference proceedings on a variety of scientific topics.
The processes of peer-reviewing of papers published in SINTEF Proceedings are administered by the conference organizers and proceedings editors. Detailed procedures will vary according to custom and practice in each scientific community.

Using inference from user attribution of models to support high resolution modelling

Jon Hand[1*]
[1]University of Strathclyde, Glasgow, Scotland

* *corresponding author: jon@esru.strath.ac.uk*

Abstract

Air flow networks are for many practitioners a *here-be-dragons* territory and despite providing useful information short of CFD assessments it has remained a niche activity. The paper discusses how we might transition from user-imposed air flows to computed air flows for long term high frequency assessments within simulation practice. It explores the historical, developmental, domain knowledge and model quality barriers to this transition. It describes the implementation of an inference facility to assist in the creation of flow networks of hundreds of entities and applies this in case studies to show what a new normal might look like.

Introduction

Few developers write about the process of designing the evolution of tools and the nature of how a diverse set of observations leads to conceptual leaps and new facilities. Few practitioners write about how they evolved working practices and found ways to drive their tools outside their usual comfort zone. And the Passive House community attempts extreme design goals with tools that are highly abstracted and would definitely benefit from access to dynamic assessments. This paper combines these perspectives – the author as a practitioner pushing multi-domain simulation projects into new territory who is a Passive House Trainer as well as one of the developers of the ESP-r simulation suite. Scores of projects involving flow networks provide the evidence of current limitations and points of frustration as well as the wealth of information that practitioners might access. They provided a rich testing ground for adaptations of the simulation tool which this paper reports on.

Overcoming inertia

In the early years of simulation practice the simulation community had to choose what to solve and often drew the line at numerical approaches to air flow. We got used to acting as *deities* who decided on a flow regime and imposed it even if it had little or no basis in physics. The *inertia* within the simulation community for the habitual use of imposed flows remains considerable. For example, in Gowri (2009) produced guidelines for adapting fixed flow approaches when building pressure tests were available. This may lead to a better match for aggregate performance but the uncertainty has always been in apportioning this single measurement over the scores of leakage paths and across time.

Compliance methods impose a range of *arbitrary* conventions which usually include imposed air flows. The risk for designers is in forgetting the arbitrary nature of such conventions. Imposing flow values taken from reference books is undermined by the evolving nature of building facades. As facades improve the energy flows associated with unintentional air movement are no longer noise in the system and have become something worth paying attention to. Imposing infiltration *as if we were deities*, is so 1990s.

There is also *inertia* in how the simulation community zones it's models. Consider the classic core plus perimeter zones for office accommodation layout shown in the Figure 1. The boundary between the core and perimeter was often an effective barrier to air movement at a junction where a host of complex and dynamic flow patterns have been observed. Enlightened practitioners might add some scheduled mixing (and some simulation suites include specific entities to enable this). Ignoring mixing or imposing guesses of mixing rates is so 1990s!

A bit of background. A number of simulation tools are able go beyond user-imposed schedules of infiltration and ventilation to dynamically solve mass flow along with other domains. Some also provide linkages between mass flow and CFD domain. Flow networks are composed of **nodes** (e.g. within thermal zones or at boundary points) and **components** (e.g. openings, cracks, fans, pumps, conduits) and **linkages.** In Figure 2 there is a room node and three boundary nodes and one frame crack, one door undercut and one extract fan which is tied into a temperature control. Typically, there is a one-to-one mapping between internal flow network nodes and thermal zones rather than a mesh of hundreds of CFD cells per thermal zone.

Each tool has its own syntax and its own approach to interacting with the user and although ESP-r is the point of demonstration the observations will likely resonate with practitioners using other tools.

Traditionally networks would be carefully planned/sketched and critical parameters and locations noted prior to inputting the relevant information for the nodes, components and linkages. Work-flows tended towards the pedantic. Clear naming of entities was assumed to provide the clarity required e.g. 'South door boundary is connected to entrance by crack-under-front-door'. Approaches to the planning and creation of flow networks are covered in (Hand 2020 Chapter 7) and http://www.esru.strath.ac.uk/applications/esp-r/.

Manual approaches work for a few dozen entities. Beyond that its hard work. Depending on the simulation tool, the facilities on offer and user skills, networks of a few dozen entities might be something to celebrate whilst other practitioners manage far greater complexity.

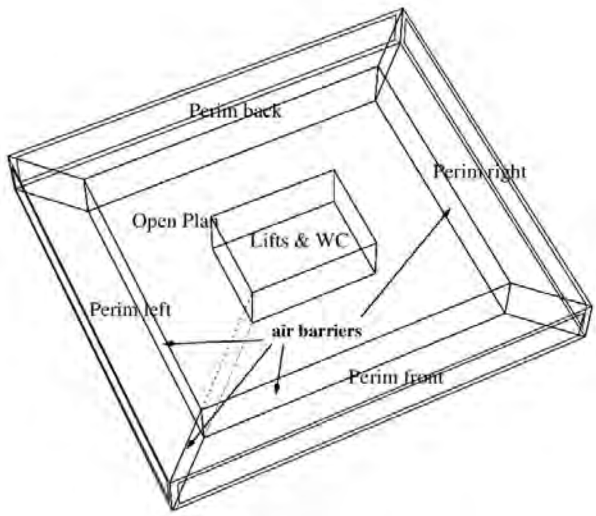


Figure 1: Classic zoning patterns

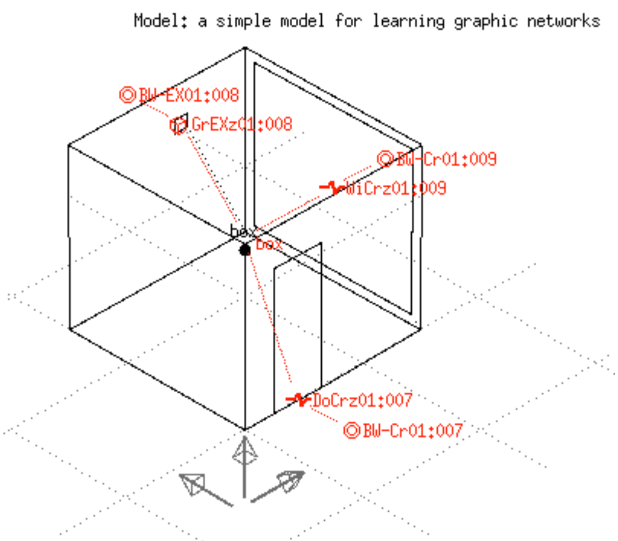


Figure 2: entities within a flow network

Regions where natural ventilation is a common design approach provided an early focus for the use of air flow assessments. Flow networks are well suited to assessing patterns and risks over long assessment periods when driving forces (wind direction, wind speed, internal conditions) vary considerably. In a UK context the majority of simulation projects our group has been involved in include aspects of natural and mechanical ventilation because they are a traditional approach to controlling overheating. In other regions natural ventilation is a niche activity and few practitioners are in the habit of using flow networks. Perhaps this hesitancy to deploy flow might be traced to the history of its development and the facilities on offer?

Historical baggage

- Much of the research was carried out decades ago with an initial flurry of interest and research papers.
- Solving mass flows is viewed by many as numerically intensive and, by inference, not to be deployed by default.
- Habits of imposed flows have been difficult to break.
- Mass flow assessments have long been associated with natural ventilation studies.
- It is littered with jargon and assumed to be used by experts.
- Tool work-flows require attention to detail. Flow is usually treated conceptually separate from buildings and systems.
- Inputs focus on the underlying equations rather than information likely to be available to practitioners.
- There is little consensus in the community as to the scope, topology and attribution of flow entities.
- Component representations are often based on curve fits for which there is no clear **provenience** or which presume access to measurements.

Methods for defining and solving mass flow are indeed decades old (Henson 1991, Walton 1989). As these methods were embedded in simulation tools there was an initial tranche of research publications. In addition to Henson's description of the solution techniques underlying ESP-r's method is also documented within the source code (ESRU 2020) and in (Clarke 2001). A terse description of the solution technique from Hensen:

The technique of is to assign an arbitrary pressure to each of the "nodes" participating in a network and representing volumes of air. The flow along each connecting branch - representing either cracks, area openings, or doorways - is the determined from empirical equations relating air flow to pressure difference. The algorithm uses a node-wise Newton-Raphson technique to iteratively adjust nodal pressures until the air mass balance equals zero at each node simultaneously. A convergence device to ensure this end result even for networks involving a mix of large and small flow paths.

The solver is highly efficient, convergence is typically reached with dozens rather than hundreds of iterations.

Having described the methods and demonstrated the facilities there were a few follow-up conference papers and a limited cohort of researchers and practitioners deployed the facilities. This pattern was repeated after air flow was introduced into EnergyPlus (Lixing Gu 2007).

Most readers of these initial review papers would conclude, not unreasonably, that dragons tended to congregate around flow networks and it just slowed everything down. Because the topic is sparsely covered in journals or in building simulation conferences such perceptions persist. Solving flow networks takes a fraction of CFDs resources and, at least in the case of ESP-r, a minimal increment over scheduled flows - for example a 40 node network solved for a two minute timestep over one week added seven seconds to run time.

It has long been an been considered an art to design a network that captures relationships embedded in a set of construction drawings or gleaned from photographs taken from a site visit. Fragmentation in the simulation community has limited the spread of best-practice guidance and thus flow networks design is a hard-won skill set.

This needs a radical re-think. At the component level practitioners are sometimes asked for values which, with a bit of digging, are possible to acquire or transform from standard sources via well documented methods. These could be revised for practitioner use. And then there are the dragon components which presume you own an entire testing lab because that is what the author of the method had access to. Here we desperately need fresh formulations.

A new normal

Looking back over a decade of projects which included flow networks a number of patterns emerge:

- computational resources are usually **not** the limiting factor in the project
- expertise tends to get re-invented rather than embedded
- there are ubiquitous instances of air flow which follow patterns and can be codified
- it pays to occasionally check the original intent of flow components
- user tasks are constrained by the time needed to envision relationships and locate gaps in networks
- simulation tools are not very good at communicating predictions of flow patterns

These projects also provide valuable usability clues:

- noticing minor user frustrations and instances of ad-hoc note taking,
- noticing points of friction that emerge at magnitude jumps in complexity
- documenting work-flows and instances of re-invention in subsequent projects
- observing what power users take for granted
- noticing that design teams are often not very good at observing air movement

The advent of widespread pressure testing provides anecdotal evidence. However, it is early days for the task of calibrating virtual flows from such tests, in part because overall leakage rates tell us little about how air distributes between rooms and via specific faults in facades. The fault detections carried out during pressure tests indicate:

- real building facades have an abundance of faults
- rain-screens hide any number of faults
- wall cavities and service voids can provide substantial shortcuts for air movement

The advent of high- performance facades has changed the rule sets. Clients are demanding more of design teams and so a number of design patterns are evolving and new classes of design questions are being asked. In order for flow network to supplant imposed flow traditions it needs to impose less friction on workflows and have a clear visibility within the simulation tool. The above bullet points suggest that we want to move the point where we can productivity deal with networks of hundreds of entities. This paper argues for and explores the pervasive inclusion of flow networks as a new normal for high resolution models.

At least for ESP-r, development tends to be incremental. The paper reports on a series of interventions by the author in the code and the data structures of the simulation tool ESP-r to transition from manual creation of the nodes and components to one based on inference. This involved thousands of lines of code, new interface menus as well as the creation of test models and eventually exemplar models for distribution.

As new data structures, menus and inference logic emerged they were tested in live research and consulting projects. Some code interventions save more time in their first use than it took to write them. Some conceptual leaps require extensive adjustments to the code that can take weeks to implement. What follows is a synopsis of the driving forces and code interventions taken.

Firstly, unlike those who have traditionally created flow networks or do blower door tests, design teams are often not very good at observing/envisioning air movement or faults in facades or in construction documents. We need another way to gather the attributes and relationships needed for the creation of flow networks.

So rather than going into a specialist facility focused on flow let's use a different point of interaction. Almost all leakage paths in a building have an analogue to surfaces and zones or system components that we have already created in our simulation models. For example, the user adds a surface representing a door between two rooms. In the past users would signal this intent via the surface name and composition. The idea is to formalize this user intent. Another conceptual leap is to notice patterns in past models and the ad-hoc notes and types of components and linkages power users.

One of the first steps was to introduce a surface USE syntax which could capture the observed patterns. Table 1 shows the matrix of the USE syntax that evolved. In keeping with the constraints of incremental development these were initially embedded in the model files as documentation.

Projects and users with access to this documentation found model quality checking was more straightforward and the networks were closer to the intent embedded in the planning sketches.

Table 1: Surface USE syntax.

Key phrase	**Implemented as**
DOOR:CLOSED	Crack around perimeter of surface
DOOR:UNDERCUT	Orifice width of door with user defined height
DOOR:OPEN	Orifice with discharge coefficient and perimeter crack
DOOR:BIDIR	Two way flow with full surface width & perimeter crack
DOOR:ADJ-BIDIR	Two way flow with constrained width and perimeter crack
FRAME:CLOSED	Crack around perimeter of surface
FRAME:VENT	Orifice following a specific rule set
GRILL:CRACK	Crack around perimeter of surface
GRILL:INLET	Fixed volume flow incoming
GRILL:EXTRACT	Fixed volume flow extract
GRILL:OPEN	Orifice with discharge factor
GRILL:DUCT	Conduit with hydraulic diameter and local loss factor
WINDOW:CRACK	Crack around perimeter
WINDOW:OPEN	Orifice with user defined area
WINDOW:SASH	Pair of orifices with user defined areas
WINDOW:BIDIR	Two way flow with full width & perimeter crack
WINDOW:ADJBIDIR	Two way flow with constrained width and perimeter crack

Next it was necessary to address the unintended consequences of focusing on the needs of the solution technique rather than clarity for the user. For example, the ESP-r flow solver requires the difference in height between components and nodes in the network but not their position in space (show image). Fewer numbers is 'good'. Flow networks were usually designed to be as simple as possible but the advent of surface USE attribution suggested rather more complex networks. We had to relax the 'fewer numbers and fewer nodes is good' mantra in order to convert USE documentation into directives used during the creation of networks and support additional views of networks.

The next step was a translation of these key words into flow components which took position, perimeter length and boundary conditions from the surface. In addition, for facade components, a matching boundary node was generated. The expectation was that the user would then traverse the resulting network to fit the specific needs of the project. This greatly reduced input errors but still expected quite a bit of input from the user.

Initially doors and windows flow components were set to match the surface area they were associated with. However, most windows do not open fully and experts would either have planned surfaces to reflect the actual opening area or edit the orifice area so it made sense to allow this kind of transform as the network was being created. Many projects included user edits to constrain the width of bi-directional flow components because many occupants leave doors ajar. This suggested that the key words to signal this as a special case.

Over several projects it became clear that users tended to impose control on doors and windows and fans and it was necessary to add parallel crack connections to the network so there was always a path to a boundary condition when the primary flow path was closed. The code was adapted to create parallel crack connections for components which could be controlled. This resulted in a more complex but future proof network.

Another conceptual leap was that as network complexity grows so does the need for ensuring the user is aware of the immediate context of a flow entity and that feedback takes multiple forms (Figure 3). Feedback to the user involved the introduction of icons on the wireframe display as USE attributes were initially defined and as well as new entries in the control menus. This reminder was critical for work flow tasks involving surface attribution. These same display facilities were used when working in expert mode within the network flow menus to remind users of linked entities.

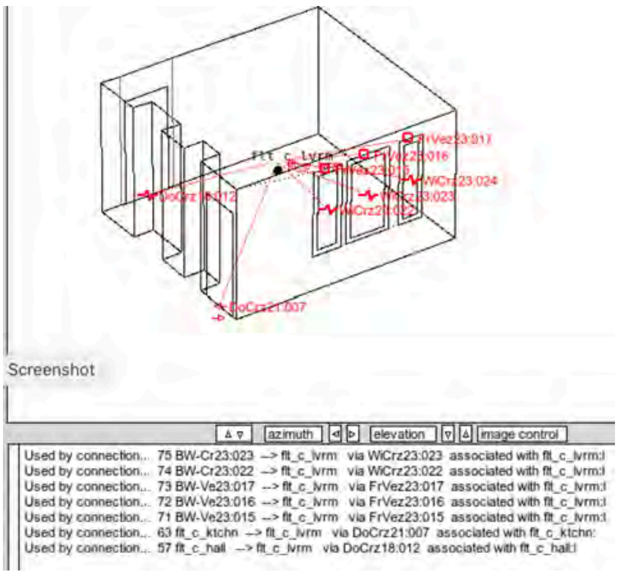


Figure 3: Zone context from within flow facility.

During the initial creation of the network the wireframe display network overlay was also updated as new entities and linkages were added. For small models and simple networks this worked but for larger models the display became overly cluttered and users lost contextual information needed for accurate editing. Another observation was that once the network had been created and the building evolved the user was forced to jump between the surface attribution menus and the flow attribution menus. It made much more sense to add the functionality within the zone surface attribution facility, as in Figure 4, to avoid the traverse and to offer the same form of feedback as was offered during the initial creation of the model. This further eased user tasks and it was possible to manage rather more complex networks.

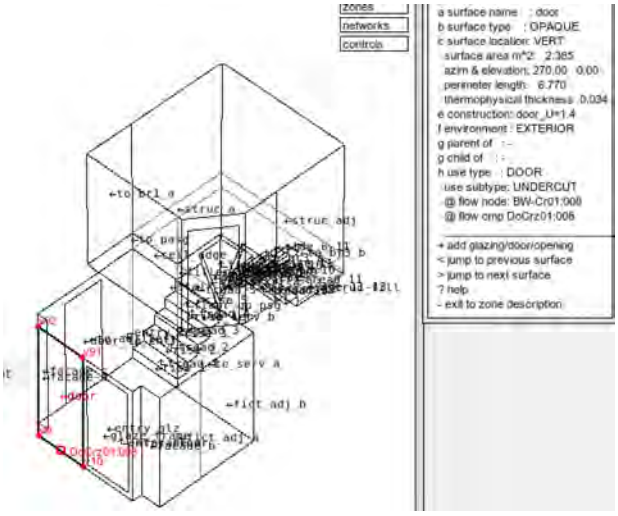


Figure 4: Context of flow components within zone.

Inference and revisiting initial assumptions

In addition to the relative straightforward bookkeeping tasks and interface updates a parallel evolution was considered for considering whether the flows resulting from the USE-to-component conversion were as expected. In the case of DOOR:UNDERCUT some unexpected predictions were found. The author had often used a crack component as 4-5mm undercuts seemed to fit the definition. Passive House suggests door undercuts of 10-15mm so that the pressure drop between rooms is typically in the range of 1Pa. However, beyond ~5mm of undercut the predicted flows were much less than found in the literature. A set of virtual experiments setup to match physical experiments reported in the literature eventually indicated that orifices would be a better fit.

Another issue was the treatment of ubiquitous element of many facades such as so-called trickle vents. Their intent is to ensure a minimal level of background ventilation. It turns out there are standard reporting conventions which provide just enough data to result in a good fit orifice and a well-documented method for converting product reports if experts wish to fine tune their network. A set of virtual experiments were setup to find mappings between published data and flow predictions. Patterns were discovered so that the inference logic could generate a fair set of initial attributes. The accumulation of inference logic is at the early stage but intent is to gradually improve the initial attribution of other ubiquitous flow entities.

The last stage reported on this paper reverts to a focus on natural ventilation. Refurbishment projects in the UK often focus on upgrading the thermal performance of facades and improving air tightness. As expected, this ratchets up occurrences of overheating and as natural ventilation is likely to be used to control overheating it needs to be included in the model. Schedule increased infiltration to mimic occupants opening windows is so 1990s!

Reviewing dozens of models where natural ventilation controls had been manually created a number of patterns emerged. The logic needs to not open windows if it is overly cold or hot outside and it is kind of silly to open windows when the heating or cooling is on. And it would also be convenient to disable natural ventilation controls by ensuring that all windows are closed. The code was extended to create a global facade control preference facility which asks a few high-level questions and then creates the relevant controls for each of the facade components. Experts could, of course, tweak these controls but the time savings in projects was considerable. Of course, natural ventilation is only one of a host of common design intents to which a software agent could have an impact.

Refurbishment Case study

A 2019 refurbishment project is indicative of the practical issues related to designing flow networks to reflect a) the state of the base case and retrofitted buildings, b) representing different ventilation ideas the design team was considering and c) finding that the assessments were tracking in the same direction as other monitoring projects. As is typical in such projects a matrix of ideas to consider needed to be tested and benchmarked against the building prior to refurbishment. The base case consisted of four two-bedroom apartments (on the left of Figure 5) and the refurbishment options included an adjacent building of the same layout which would have an external insulation system applied to all of the apartments. One flat would also have a mechanical extract system and floor heating, another would have the vent system plus skirting board heater, as in Figure 6, and one flat would have the mechanical extract system with a mix of skirting board and conventional radiators.

Figure 5: Base-case and refurbished apartments

The mechanical extract was intended to improve indoor air quality and control humidity levels. To limit costs extracts were only connected to the main living space, the kitchen, bathroom and passage and humidity sensors would open dampers into the main extract chamber. Thus, there were many possible combinations and the pressure imbalance created also influence inter-room flows. The idea was also to use humidity-controlled facade vents.

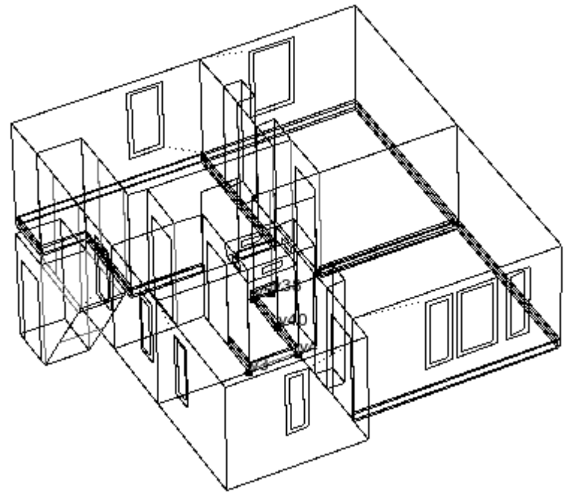


Figure 6: View of flat with explicit skirting board heaters and extract system

A number of refurbishment ideas required explicit representations so the extract mixing boxes, crawl spaces, roof voids, heated floors sections and skirting heating units were treated as separate thermal zones. Considerable diversity was enabled for occupants and humidity generation in various rooms which lead to some obscure corners of the internet to discover heat and humidity associated with various cooking and bathing activities. The resulting model comprised 75 thermal zones. Additional surfaces representing the grills and the casing of the skirting heating and floor structure were included to support detailed comfort assessments. There were 50 room controls to accommodate the various heating regimes and 20 controls for flows associated with the extract system. The flow network included 238 nodes and 253 components - somewhat greater complexity than would have been common a few years ago.

To support the study a virtual test chamber was setup to find a set of component attributes that matched the published pressure drops for the facade vents but it was not possible to find full details of the control logic used in the extract system. Flow controls traditionally sense temperature or humidity but not both so a more complex network was required. There were no pressure tests available so it was not possible to calibrate the facade faults included in the model.

The report to the client focused on the following metrics:

- Peak capacity of heating equipment
- Energy demands over time
- Distribution of temperatures within the flats
- Hours over 25C in each of the rooms
- Response during cold periods
- Frequency of ventilation boost rates (Figure 8)

The findings of the project report related to flow were:

- The design largely suceeds in improving indoor air quality and limiting humidity buildup.
- In cold conditions there is a risk of draft and compensating heating demands.
- It provides only limited overheating protection and trickle vents are marginal in summer conditions.
- Huidity remains high in bedrooms if doors are closed.
- A façade upgrade without addressing ventilation issues lowers heating costs but results in generally lower comfort and air quality.

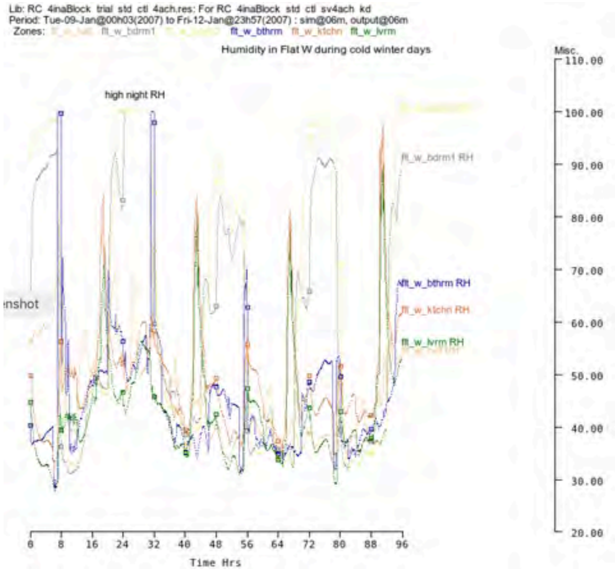


Figure 7: Humidity levels in bedrooms

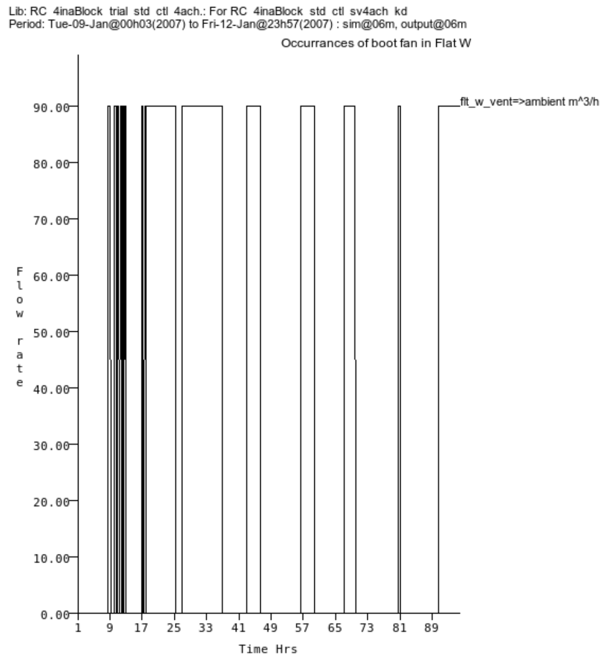


Figure 8: Instances of ventilation boost fan

Although officially sanctioned the efficacy of trickle vents has been questioned in many studies. When combined with closed doors to bedrooms the reductions in flow had clearly detrimental impacts on air quality and humidity. Revising the model to add extract grills in the bedrooms mitigated much of this risk but would have required more inlets than the extract manifold was designed for. The other finding was the moderating impact of at least partly opening the door between the kitchen and living area. Overheating from cooking was dissipated more readily and helped compensate for the limited heating capacity of both the floor and skirting board heaters.

Resilience testing case study

Some projects are focused on the resilience of buildings, for example, looking for instances of discomfort if particular failures happen in the fabric or operation of a building. Design teams identify what metrics, at what frequency would signal failure. The building is continuously assessed and subjected to random faults at random points in time to see if the expected standard of performance is maintained. When failures are detected the further investigations can be invoked. Air flow assessments are well placed to cope with such continuous assessment scenarios. The 'further investigations' potentially need higher resolution and here is where a mix of air flow and CFD assessments can be used.

A design team was concerned that one of their high performance housing designs (Figure 9) might be at risk from overheating and so a high resolution model (Figure 10) was created with a flow network in place which had been designed to support natural ventilation for overheating (30 nodes 34 components and 34 connections). The model also hosted CFD domains in the primary rooms to support detailed assessments without the overhead of domains in minor spaces. In ESP-r CFD domains are tightly coupled to air flow networks as well as thermal zones and adapt at each timestep to new boundary conditions.

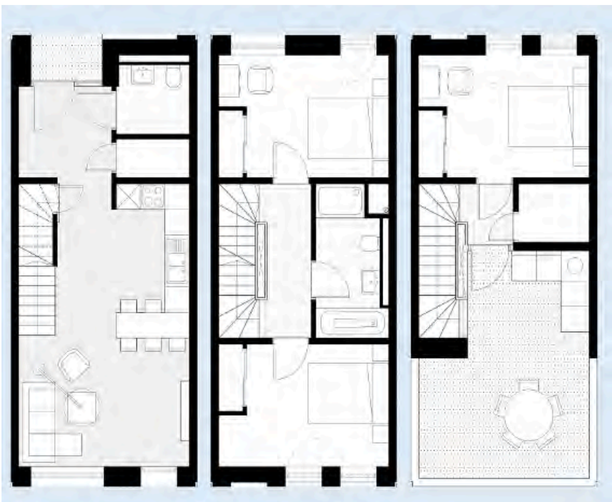


Figure 9: Terrace house for overheating risk assessment.

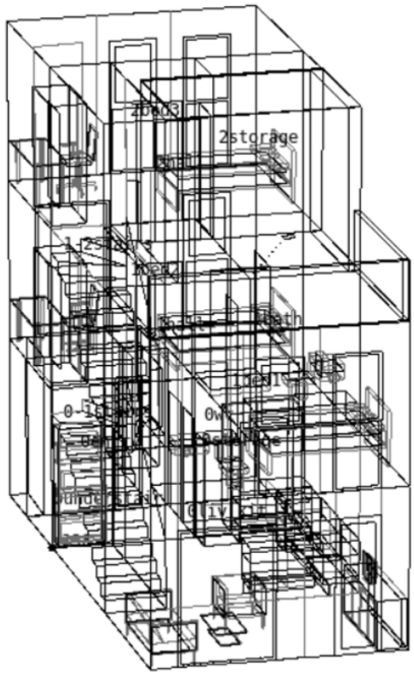


Figure 10: ESP-r model of the house.

Detailed assessments would typically look at patters over a few days at 10 minute interval. Figure 11 shows flow patterns, temperatures and CO2 concentration in the kitchen/lounge.

Skills acquisition

The approach taken requires practitioners to notice and attribute surfaces within the model. Users need a bit of background as well as hints gleaned from power users (but with the jargon stripped out). There are a number of steps in the process that needed to be documented and it became clear that this worked much better if a number of sessions were captured and then annotated. Users have access to:

- A web page with guidance on how to survey buildings with multiple worked examples and videos of the process of creating networks.
- Exemplar models have been updated or added which demonstrate a number of classic use cases.

A number of practitioners have used the new facilities and the author found fewer faults in these models and also noticed that they were somewhat more complex than those users had managed in the past.

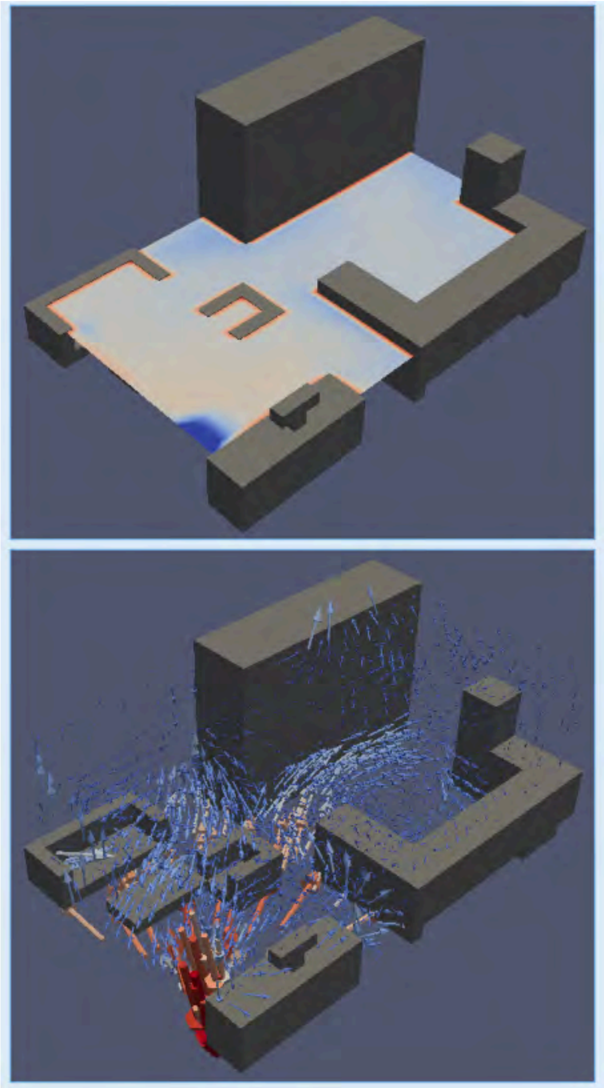


Figure 11: CFD plots in primary rooms.

Conclusion

The approach taken in the work reported is requires that users signal the use of entities in the model. The tool makes inferences which should result in a well-founded model but, crucially, the user gets a veto over what has been generated. Full details are reported and it is assumed that flow experts will be tweaking the network to match their opinions.

The nominal complexity of models has shifted by roughly one magnitude and it is possible now to consider applying air flow assessments within less constrained projects. An ongoing project is looking at eight different construction types in a new neighbourhood of 48 houses with physical and virtual tests carried out on a sample of a dozen houses. Modelling of each room in those dozen houses requires roughly 100 zones and including a mix of mechanical vents and window openings is going to roughly push the network complexity to 300-400 nodes and components.

Parallel work is underway to streamline the creation of CFD domains within ESP-r. Currently users have a number of 'rules' that they need to follow and additional specifications and linkages which must be supplied. The long-term aim is to lower both the friction and expertise needed to work with CFD domains.

This paper has not discussed the state of other simulation tools which feature air flow solutions. Some hide the networks that are created from users. What a strange decision in light of practitioners need to carry out due diligence.

Other tools also have historic baggage that has limited the up-take of flow assessments. The Gu (2007) paper includes a horrific chart showing the relationships between flow related entities for EnergyPlus. Names and numbers for flow entities in IDF files use a different syntax from the legacy flow network files of ESP-r but their focus on feeding the underlying equations obscures how they relate to the building and limit graphic presentation options. See how far you get in five minutes reviewing the simple EnergyPlus house exemplar AirflowNetwork_MultiZone_House_FanModel.idf?

It will be interesting to see the extent to which practitioners are able to leverage the ideas and facilities discussed in this paper and what further evolution might be required to make user imposed flows a niche activity.

Acknowledgement

I would like to thank the other practitioners using flow facilities for contributing observations used in this paper.

References

Clarke, J.A. (2001). Energy Simulation in Building Design, Second Edition. Butterworth-Heinemann. (UK).

Gowri K., Winiarski D., Jarnagin R. (2009). *Infiltration Modeling Guidelines for Commercial Building Energy Analys PNNL-18898.* Pacific Northwest National Laboratory, Oak Ridge, TN (USA). https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-18898.pdf

Gu, L., "Airflow Network Modeling in EnergyPlus", 10th International Building Performance Simulation Association Conference and Exhibition on September 3-6, 2007 in Beijing, China

Hensen, J.L.M. (1991). On the thermal interaction of building structure and heating and ventilating system. Glasgow. (UK).

Hand J. A. (2020) Strategies for Deploying Virtual Representation of the Build Environment http://contrasting.no-ip.biz/Strategies/Index.html