A natural ventilation “calculator”: The challenge of defining a representative ‘performance sketch’ in practice and research

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Abstract. Too often in architecture and engineering, the simplicity in early design of the apparent guarantees of HVAC equipment manufacturers wins out over the complexity of estimating the effectiveness of natural ventilation even in Net Zero Buildings. The reality is many people in offices and schools find themselves sitting at a fixed desk, in full direct sun, with the cold draft from the HVAC equipment guaranteeing that on average they are comfortable. The drawing of blinds ‘solves’ the immediate sun problem, but not the quality of the air. Experience with 200+ students designing low energy, high performance naturally ventilated spaces each year over the past decade has demonstrated that the formulae that exist in the literature for early estimation of window opening size have potential if presented in an appropriate format to facilitate sound design decisions. This paper reports the evolution of that format to a calculation dashboard that facilitates accounting for: outdoor and indoor CO2 levels; wind speeds and frequencies of occurrence; coincidence of periods of calm with high outdoor temperatures; window effectiveness coefficients; single-sided vs cross-ventilation options; building shape and orientation; code minimum ventilation rates; and even infiltration. The paper focuses on the limitations of the approach and its potential complementary role in the future as a Quality Assurance tool for critiquing the output of CFD studies of natural ventilation.

1. Introduction

In the development of environmental design decision support tools (eddst) there is a common assumption that design teams do not use currently available tools because they answer the wrong questions: “...there are serious doubts to assuming that more architects and engineers will design buildings that exploit natural lighting if only they are provided with the requisite information and design aids ...” \cite{1}, \cite{2}. The objective of this paper is to report lessons learned from educating undergrad students about the types of questions that design teams wish to have answered where eddst’s \cite{3} could be of assistance. This paper reviews lessons learned about early design simulation from a decade of classes for architecture, building science and interior architecture students numbering over 200 per year and focused on simulating the thermal, acoustic, and daylight performance. The class is offered in the second year of a student's studies.

Its starting point is survey results that show that architects are in fact interested in creating environments of thermal, visual and acoustic quality \cite{4}. This is contrary to the oft-suggested notion that architects are not interested: “It is a telling commentary on the current situation that architects must now be convinced that it is no mean achievement to design buildings that function well” \cite{4}. The architectural design problem has for centuries been one of developing ‘models’ of the built environment. Models have in the past been: mathematical models such as representing heat loss as R-values; physical models such as used to study daylight under artificial skies; and diagrams like the Psychrometric chart or the Waldram sunpath and daylight factor representations \cite{5}. This paper examines the single biggest barrier to general use of detailed eddst’s: if one is an inexperienced user of a comprehensive tool, how
do you determine that its predictions can be trusted. This applies equally to the educational environment in this case study and to the architect-practitioner who is not a regular user of the eddst software.

2. The research question
This paper examines Quality Assurance (QA) issues associated with eddst’s that simulate natural ventilation. QA, in this instance, is systems designed to improve trust in predictions. The issue facing the educator is that the lack of general use of eddst’s early in architectural design has several root causes that must be a part of the educational approach. These are:

1) The tools are often too simplistic. Researchers simplify a rigorous performance prediction equation or set of equations to the point where they judge if they will be acceptable to architects. The desire for simplification in the form of a ‘rule of thumb’ from designers and their professional associations [6], [7] too often trivializes the issues. This renders it impossible for design teams to predict or systematically document building performance [5]. Eventually, the simplifications make the performance model so remote from reality that the tool is irrelevant. The continued popularity of the Daylight Factor despite clear knowledge that for the past 50 years it has encouraged windows to be the same no matter which compass direction they face illustrates this issue perfectly. Nils Antoni [8], sums up the problems with this approach wrote in 1986: “I am suspicious of selected, processed information. It is a last resort... One never knows what criteria lie behind the choice made and how competent those doing the processing are...” Educator lesson: simplistic rules of thumb, on their own, mislead.

2) Where a project is of sufficient size to have an expert design team, the environmental design experts in the design team often are ineffective in relating the environmental design issues to the interests and concerns of the architect. The causes of these problems are many. They include the oft-quoted lack of reading by architects of anything more complicated than a child’s picture book [9], [10]; individual environmental design analyst’s inability to focus on the whole design rather than their one area of expertise; and the difficulty of establishing a good working relationship in a design team where the professional and financial rewards for team members may well conflict. Educator (of architects and building science analysts) lesson: ensure sound understanding of the metrics of environmental performance and how they are predicted / estimated in order to facilitate communication.

3) Beginning with the lessons learned from the USA 1980s passive solar commercial building design research programme [11], eddst researchers often state that early design decisions determine building performance [12], [13]. As building performance simulation (BPS) enables detailed and systematic design parameters to be related to occupant comfort, the lesson for the educator is that designers and analysts both need to have experience in creating quick environmental performance sketches, prior to the architectural sketch, that use BPS to evaluate building performance quickly but in-depth.

4) Eddst’s are argued not to be in sync with designers’ ‘intuition’. It is true that in a world where often a 3D sketch of a building is the input to the energy and ventilation model, it takes some considerable experience not to see the hole in the floor where the stairs are to be placed as a path that air will flow through. It is a surprise that the eddst must be ‘told’ the air flow characteristics of that ‘hole’ through explicitly entered input data. Even expert analysts’ ‘intuition’ has been found to be insufficient [11]. BPS software is argued to be simply too complicated and thus not ‘architect-friendly’ due to the differences in language, modelling processes and visualisation of results [14], [15], [16], [17]. It is suggested that BPS based eddst’s can only be used when the design is sufficiently complete that the detailed building specification required by the performance calculation is available. In education, one does the design, then later, often in a different educational course, analyses its performance. In education, with this approach, one never learns how to design in response to performance evaluations. In a design practice, the results are even more catastrophic: by the time the analyst has the full information from the designer to do the detailed analysis, it is too late to change the fundamentals of the design in response to the performance feedback. [12], [18]. The lesson for the educator: intuition will develop from learning through sketch performance analysis the connection between detailed performance metrics and design decisions.
3. The research context

How can the designer ensure that the building will perform as intended? Many papers suggest that the first step should be to ensure the ‘architectural sketch’ will lead to good building performance [19], [12], [20], [13], [21], [22]. The advantage of computer-based edd’s creating a ‘performance sketch’ is that the feedback is far more relevant than comes from a simplistic ‘rule-of-thumb’; or worse, from an ‘architectural precedent’ building design that is argued, often without proof, to work in another climate or social or cultural setting. Increasingly, interactive ‘parametric’ environments are being promoted that allow the user, student or professional, to drag a building element and ‘watch’ the energy use or daylight level change instantly. The only way these can operate in this manner is to base them on simplistic rules of thumb developed almost 100 years ago. Daylight patterns for some mythical overcast / sunny representative ‘days’ and ‘times are a common problem where these ‘tools’ do not differentiate between North, South, East and West windows because the Daylight Factor rule-of-thumb cannot.

In this undergrad class, a less obvious, but equally critical, problem has been found to be designing windows for ventilation. Typical hand calculation formulae [24] allow estimation of stack effect, calm day air transfer or windy day transfer. These are obviously limited. They assist the user to figure out how big a window needs to be. The manner in which natural ventilation is often dealt with in edd’s based on thermal simulation is often more detrimental. This is because it is common for the BPS user to enter a number into the program that is the estimated maximum air transfer rate for that window, and then to set a trigger point temperature above which the window opens. This results in the mindless BPS computer calculator ‘opening’ a window and calculating the effect of the assumed 10 or 20 Air Changes per Hour (ACH) on the internal air. At times, say when the temperature is just 1 degC above the set point, the room cools way below what is needed. This is not an accurate picture of how people might really open a window just-a-little if the room is slightly-too-hot. Nor does it help the designer to assess how big the window openings need to be to deliver this amount of air. Students quickly see the flaw in this which begs the obvious question: how can they, or their professional colleagues, design naturally ventilated passive energy buildings?

4. Lessons learned from modelling thermal performance in detail

The disadvantage of running a course focused on developing intuition and understanding of human – environment interactions through simulation is that the students often focus on the skills conveyed in the tutorials. This is a continuing perception problem.

An external review of the course during its first two years reported that the biggest barrier to learning was the time-consuming work of direct translation of designs from a design studio to the analytical BPS tool. Nearly 10 years later, despite the promise (hype?) of BIM, this translation remains a major time drain in design practices, as well as in class. The course now focuses the students’ learning on the intellectual challenge of defining a representative ‘performance sketch’.

The external review also commented that the single most important step to encourage integration of the content of simulation into the design programme was for the tutors in the design studio course as well as those in this analysis course to engage students on what performance they should simulate. The tutorials for the projects therefore focus on 3 issues: week 1 – defining appropriate performance metrics that relate to the design studio goals; week 2 – developing a simple BPS performance sketch that can predict this metric for the passive design ideas that the students wish to explore; week 3 – running at least 3 design variants and Quality Assuring (QA) the BPS predictions. Once a performance sketch is working, rapid design option exploration is remarkably quick and easy.

In the mild climate for which these students are designing, natural ventilation through opening windows is an ideal cooling system. Any other cooling system is significantly more expensive to install and maintain. The problem for the building performance sketch analyst, and thus also for the students, is that simulation tools can take a range of different and complex approaches to modelling natural ventilation. Learning to use one well, could take much more than a 3 week BPS application seminar. They are in fact well beyond the means that many clients are willing to devote to this analysis. At present, for example, CFD can be the focus of graduate classes and a specialist analytical service for complex buildings. Each year, this course has had to become more and more explicit about two issues related to natural ventilation modelling:
1) Assisting the students to use realistic ventilation input data to test natural ventilation feasibility;
2) Enabling the students to formulate their own answer to the constant refrain of simulation students: “Is this [performance prediction] ‘right’?” Helping them to trust the data.

These two challenges apply as much to the consultant or the graduate student completing performance sketch analysis as it does to this introductory course.

5. A tool to assist QA in modelling Natural Ventilation as part of Building Performance Simulation

The focus of early design ‘performance sketch’ analyses is to get the building running well before the next stage of analysis examines the fans, pumps, motors and boilers/chillers of a full HVAC system. Students do not deal with simplistic energy balances. The focus is on the design of the building fabric to achieve maximum comfort. They plot statistical patterns of temperature variation appropriate to the design goals across the whole year – a balance of R-values, heat capacity, window area, size, and orientation, plus operation of windows for cooling.

Here, what the students face is the common dilemma for all consultants wishing to model naturally ventilated buildings: building a realistic model of the air flow, and the devices that promote it, such as windows, but also ventilation chimneys and atria. Questions that regularly arise are: What are the wind pressures that affect the window function? What is the effect of thermal stratification? What are the coefficients that measure the effectiveness of the window functioning? How can cross ventilation be adequately represented through doorways and corridors? The list is almost as endless as it is frustrating.

The evolution of the ventilation calculation process in the course has reached the stage where a ventilation calculator has had to be developed. The process for the students over this time has evolved. At first, in line with common practice in the earlier years, the students were advised to enter the potential ventilation rate as a large Air Change Rate. Because these ACH values were estimates, based on research publications, QA for the design required entering data for a low and a high estimate to check the robustness of the design conclusions.

Over the years, these design conclusions have become more complex. First, the students were provided with a process of improving the design relevance of their BPS temperature calculations. This was a calculation procedure mined from a wide range of alternative design or sizing formulae that exist in the research literature [23], [24], [25], [26], [27], [28], [29], [30]. The procedure enabled them to attempt to estimate the size of window needed to provide the Air Change Rate included in their BPS calculations. The manner of their presentation is opaque to most design professionals, so the books on their own were not helpful for an introductory thermal principles course.

More recently, as the the QA processes necessary to produce reliable window design sizes became the subject of some of the A+ students’ inquiries, it became clear that the simplistic wind pressure coefficients in tables for simple building shapes documenting the likely effect of wind on ventilation was insufficient. The students are clearly aware, as are most consultants, that the general data typically do not represent their building shape well. In fact, they seldom represent the effect of the surrounding buildings on these pressures either. Questions about the ‘coefficient of discharge’ for particular window sizes or placement or the degree to which it is propped open?

Practitioners and students alike recognise they have run thermal simulation for the whole year knowing the temperature, humidity, wind speed and solar radiation combinations are unique for all 8760 hours in the year. The ‘obvious’ answer for those familiar with BPS natural ventilation models would be to stop using the simple ACH model. Unfortunately these suffer many of the same unknown coefficients issues as manual calculations.

Common to manual or computer-based thermal simulation are decisions about:
1) how to define a height for the difference between inlet and outlet for the stack effect to function;
2) how to define inlet and outlet appropriately to ensure the cross-ventilation flow occurs through the occupied zone;
3) how to select appropriate wind speeds and directions to account for the wind pressures on each façade of the building driving the ventilation (only some thermal simulation programs allow entry of a set of pressure coefficients for each building façade that are different for each wind direction);
the definition of opening area, and the effect of wing walls beside the windows on the likely
effectiveness of each different window type is sparse in readily accessible literature.
In all these situations, whether manual calculation or simulation based, the inevitable student question,
that ought to be asked by every consultant after each calculation is highlighted as a critical unanswered
issue: “Is this prediction ‘right’?”

6. Conclusions
The three week simulation exercise has students use a solar-driven, hour-by-hour, annual thermal
simulation tool: SuNREL (from NREL). They are required to establish Fanger/Adaptive comfort
performance metrics themselves. If the reported free-floating internal temperatures given their assumed
ACH rates are always under the target temperatures, then the cooling power of the windows is adequate.
If maximum temperatures require very high airflows, then there are some serious issues to be addressed
in the provision of cross-flow ventilation with very large openings. If there are still serious overheating
issues, then the climate may be unsuitable for natural ventilation cooling all year. Relatively simple.

The next part of the feasibility calculation is to establish whether the windows can be opened
wide enough to provide this air flow. Running an hour by hour dynamic thermal simulation often takes
no longer to enter the basic building data, but provides more than an annual energy estimate; it provides
8670 hours of temperature and humidity data for statistical analysis.

To calculate the window area required to deliver the air flow to meet the maximum need for
cooling, a spreadsheet calculator has been created that enables the students to enter some simple
volumetric information, select from a pictorial guide of window openings relevant ‘discharge coefficients’
to estimate required window areas for rooms with openings on one side or for rooms with
cross-ventilation. They can select different published formulae for this estimate by clicking an
alternative model button. This is used to ascertain Quality Assurance feedback on how important the
assumptions in this model might be.

In order to facilitate Quality Assurance that applies to the whole thermal simulation the
spreadsheet has been developed so that it also permits rapid manual (DegreeDay based) estimation of
heat loss. This ensures each simulation is in the right “ballpark”. A recent graduate exercise modelled
an apartment in EnergyPlus where the amount of CO2 generated by people indoors was diluted by natural
ventilation using outside air plus custom window opening controls for when CO2 was too high. There
was however still a great need for a Quality Assurance tool to establish a level of trust with the (now)
very complex network flow model in EnergyPlus. The simple natural ventilation calculator developed
in the undergraduate course to facilitate performance sketch analysis provided this necessary Quality
Assurance.

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