La 5e conférence d'IBPSA - Canada
The 5th IBPSA - Canada Conference
Québec 21-22 mai

# COMPARISON OF TOOLS FOR DESIGN AND PERFORMANCE PREDICTION OF PASSIVE DESIGN ELEMENTS

Derek Whitehead[1], Duncan Phillips[2], Vadim Mezhibovski[2], Meiring Beyers[2] and Andrea Frisque[1]
[1] Rowan Williams Davies and Irwin (RWDI), Vancouver, BC, Canada
[2] Rowan Williams Davies and Irwin (RWDI), Guelph, ON, Canada

## ABSTRACT

In the present paper the design process for a number of passive design features is described – daylighting, passive solar heating, natural ventilation using a solar chimney, and a double shell roof - is described from both a technical perspective and the aspect of integration with the design team. Example results from different tools are shown and interpreted. The limitations of different simulation approaches are explained. It is shown how the different parts of the engineering analyses complement each other and work together toward high design confidence. It is discussed how the results of the engineering studies are used to inform the design team and help them make informed decisions. On each project this is always a mutual learning and understanding process of the design goals and the technical possibilities and risks.

## INTRODUCTION

One of the fundamental aspects of sustainable design is the exploration of passive design elements. Before mechanical (and electrical) systems are explored to satisfy building needs, passive features can be used to reduce building conditioning needs. Passive design can consist of straightforward considerations such as improved envelope performance – highly insulated, tight walls, high performance windows, reflective roofs, thermal mass and more. There are also more sophisticated passive design elements dedicated to improve air flows through the building and improve the heat transport properties and paths inside the building, such as for example wind towers, solar chimneys and Trombe walls. These elements can be used to extend the range in which it is possible to provide comfortable conditions without mechanical conditioning.

Designing passive building elements is a challenge to North American building design, which has traditionally been focused on designing mechanical and electrical systems for given building shells or building designs rather than designing the building's performance itself. Designing the thermal performance of the building rather than the mechanical systems requires a different set of skills and tools than mechanical systems design. Knowledge of fundamental heat and mass transfer is required, and proficiency with using related tools such as for example air flow network models, computational fluid dynamics (CFD), finite element/volume heat transfer and zonal whole building thermal models. These tools are used to evaluate critical design conditions as well as to predict overall yearly performance of a proposed building design.

Passive design elements as described above have been proposed to reduce building energy consumption in the 1970ies and have been built and tested, typically in small buildings. However, partly due to the complexity of the calculations necessary, tools to design passive building elements are only in the process of being developed, but are not widely accessible and used yet. An earlier example is Afonso and Oliveira (2000), and recently there has been increased activity in the area of prediction of the performance of passive design features, see for example Miyazaki et al. (2006), Gan (2006), Macias et al. (2006), Jle et al. (2007), Burek and Habeb (2007), Shen et al. (2007), and Bacharoudis et al. (2007).

This is particularly true for the interaction of such passive design elements with larger buildings and developments. Predicting the integrated performance of a building of larger scale than single family residential with a passive design feature such as a thermal chimney or a Trombe wall in interaction with its climatic environment is not a routine task. With the renewed and increased focus on energy efficiency and the newer concerns about carbon emissions these building elements are attracting attention again as components of sustainable, "green" buildings, and this time not only for small developments. Natural ventilation, possibly combined with passive solar systems such as Trombe walls and solar chimneys, ventilated double shells, wind scoops, transparent and translucent envelope elements for daylighting, architects are exploring the possibilities of including all these features and more into large-scale, sustainable buildings. Engineers are challenged to provide design teams with information on the performance of such features: what can be predicted, what are the limitations and uncertainties in the methods used and what are the risks included. In this paper, after introducing the design tools used, we describe a few design examples with respect to which engineering analysis tools were used and the interaction with the design team. As passive building elements become a part of the building, integration of building thermal comfort performance and energy design, and development of the architectural vision are intrinsically intertwined to maintain form and function.

## INTRODUCTION TO THE ANALYSIS TOOLS USED IN THE DESIGN PROCESS

In the present paper, the design challenges faced by the authors in several projects are summarized along with a description of the approach taken to develop solutions. This section describes the types of tools and specific products that were used.

Daylighting software covers a wide range of tools that satisfy a wide range of requirements. Ecotect is a software program that allows the user to quickly develop a three-dimensional representation of a building. Users can perform a wide variety of analyses; in the studies described below the modules for solar exposure, shading and natural lighting are used. The geometry and surface material descriptions of models built in Ecotect can be exported to RADIANCE.

RADIANCE is a software package that can accurately calculate and display visible radiation in illuminated spaces. This ability is particularly useful when designing spaces to be naturally illuminated. Snapshot images with corresponding luminance and illuminance surface values can be generated for specified sky conditions.

One of the drawbacks of RADIANCE is the long computation times. Snapshots of room lighting under specific sky conditions are useful, but often say little about the anticipated daylight levels throughout a typical year. To obtain this information, one can use a daylighting analysis tool called Daysim. This software uses the RADIANCE algorithms to efficiently calculate annual indoor illuminance and/or luminances profiles based on a weather climate file.

WINDOW 5.2 is a computer program that can calculate total window thermal performance indices (i.e. U-values, solar heat gain coefficients, and visible transmittances). This software can access the international glazing database, which contains spectral properties for over 2300 glazing products.

Integrated Environmental Solutions Virtual Environment (IES VE) is a software package that allows for a wide variety of analyses. In the studies described below solar gain calculations, dynamic thermal simulations using zonal models and nodal network air flow models for bulk air flow movement calculations are used.

Nodal network air flow models coupled with zonal thermal models – such as IES VE and EnergyPlus/Airnet - are useful in many cases to estimate bulk air movement rates between zones separated by relatively small openings (e.g. open doors and windows). They can still be used when opening sizes are much larger, but predictions become less accurate. Nodal network air flow models also assume that the air does not carry momentum through spaces. For situations were knowledge of fluid motion within and around surfaces is required, computational fluid dynamics (CFD) can be used. CFD solves the fundamental thermo-fluid dynamic equations describing heat and mass transfer in the spaces: conservation of mass, momentum and energy. CFD simulations resolve the air velocity and temperature field inside spaces, as well as long-wave radiation fluxes between surfaces and incoming short-wave solar irradiation. In this way CFD uses numerical methods and algorithms to improve an understanding of fluid flows. For the project work described in this paper, FLUENT is used for CFD analyses.

## EXAMPLES

**Daylighting, Thermal Comfort and Cooling Load in an Atrium in a Hot Climate**

In this example, the design team was presented with the challenge of providing as much daylight as possible through skylights into a three storey atrium containing open offices on the periphery. The configuration is schematically shown in Figure 1. The building location is in an extremely hot and humid climate, so cooling load reduction is also important. The project was fast tracked, so assessment and feedback had to be quick.

Initially, various opening configurations and shading options were proposed and investigated. Building geometry was constructed using Ecotect, then exported to RADIANCE to provide luminance and illuminance predictions for snapshots of specific dates and times. As well, Daysim was used to provide annual statistical information to assess the frequency of various illuminance levels on the ground floor.

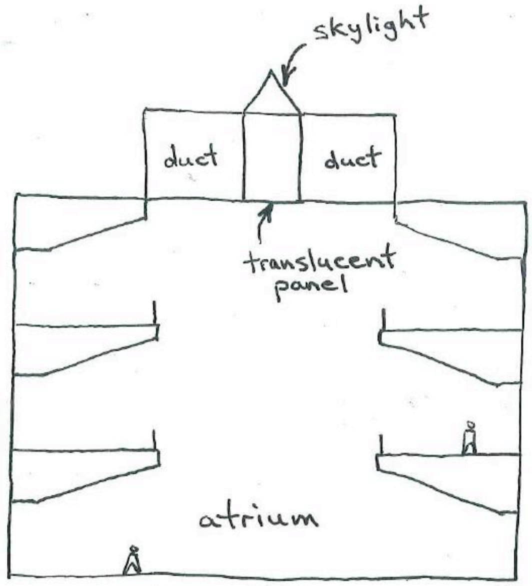


**Figure 1: Atrium configuration.**

When the first results of the initial simulations were discussed with the client, including description of the input in the simulations and how models are built, it became apparent that there were more features of the proposed design outside the space, on the roof, that needed to be taken into account. This example illustrates how important it is to review work in progress with the design team in order to both provide and gain a better understanding of simulation models in order to maximize their value. The daylight simulation models were extended to include the additional roof details, consisting of large ductwork on the roof above the atrium. As a result, the area admitting daylight was restricted between long and relatively narrow openings between quite high ducts. This situation demonstrates how easily important design criteria or constraints can be overlooked in a fast paced design environment and stresses the importance of communication between team members.

Subsequent RADIANCE and Daysim results demonstrated how illuminance levels would be quite low most of the time. The only occurrence of moderate illuminance levels was when direct beam sunlight could strike the ground floor during midday. At these times, there was a high potential for glare and unacceptable thermal comfort levels for occupants in the direct sunlight.

A few complete design solutions were developed with the design team. It is not yet decided which option will be implemented; the process of considering all the implications is still ongoing. One solution to this challenging design problem that performs particularly well from a daylighting and thermal comfort perspective, but does change the exterior appearance of the building, is the use of an angular selective skylight along with a translucent panel at the ceiling level. With this arrangement, sunlight directed down the shaft from roof to ceiling level would be increased during low sun angles and decreased during high sun angles. All sunlight entering the atrium would be scattered somewhat uniformly from the translucent panel.

RADIANCE was used once again to demonstrate the effectiveness of the translucent panel without the spectrally selective skylight at various sun locations. This information was combined with manufacturer's information on skylight performance throughout a typical day for various times of the year at this location to develop predicted daylight performance in the atrium.

In this example, Ecotect was used for a first RADIANCE input file. Because of the limited control of RADIANCE through Ecotect, the RADIANCE input file was then extended by hand for further RADIANCE runs. No RADIANCE model for angular selective skylights was available, therefore the influence of the angular selective skylights was calculated by hand based on manufacturer's test data.

**Passive Solar Heating**

A team designing a multi unit residential building in a heating dominated climate was interested in exploring the options for passive solar heating. In the early stages of conceptual design, a lot of discussion ensued about design features such as large windows facing south and smaller windows facing north. However, as units are not spanning across the whole floor plate, but there rather are also units facing either the south or north, there was no potential for aggressively reducing window areas on the north facing façade. For all façades other than the south facing one the window-to-wall area had already been minimized to the smallest amount that would still allow for comfortable suites in order to minimize heating loads. The remaining question was whether it was beneficial to increase the window area on the south façade or not. To answer this question a dynamic thermal model was built in IES VE. This model was used to compare the heating loads for a window-to-wall ratio of 40% for the whole building, and a number of variations for a building design where this ratio is increased to 70% for the south facing façade only. The results are shown in Figure 2. Iincreasing the window area on the southern façade without including additional design measures did not decrease the heating load but rather increased loads, meaning that the additional solar gains could not offset the additional losses particularly during the night time. Increasing the exposed thermal mass in the residential suites has a positive impact, though it still does not offset the increased losses. When the thermal mass impact was discussed during design meetings, the design team realized that they had to take into account the extent to which they could rely on future building occupants to engage into the operations of the building, as large amounts of furniture, carpets and rugs, and other items inside the suites would impede the proper function of exposed thermal mass.

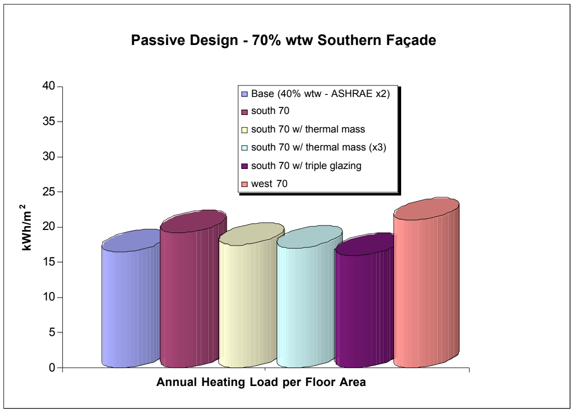


**Figure 2: Example heating loads for an initial feasibility assessment of passive solar heating without optimizing building floor plan lay-out.**

In addition two further cases where simulated, one with increased glazing performance demonstrating the large impact of the windows on the heating load, and rotating the façade with the 70% window-to-wall ration to face west. This latter simulation was included for demonstration purposes, because, as much as it is clear to engineers and related professions that passive solar design in temperate to cold climates is a delicate balance and southern exposure is crucial, this is not necessarily clear to all members of an integrated design team. Simulations are a powerful tool to show people the impacts of their design choices. The results shown here helped the design team to understand what it takes to make a passive solar design work, and as changes in the floor plans, large exposed areas of thermal mass, changes in usage such as for example not heating bed rooms during the daytime were not realizable for the present design, passive solar design was not pursued but the focus was rather shifted to highly insulated façades, reducing window areas as far as feasible, avoiding thermal bridging and such measures. The simulations were critical in supporting the design team in making a decision.

The simulation tool selection was based on two criteria. Firstly, the emphasis was on passive features rather than systems, so a DOE2 based tool did not seem like a first choice, but rather a tool that calculates heat transfer in the walls directly. This still leaves several choices, for example EnergyPlus/DesignBuilder would have been just as good a choice from this technical perspective. IES VE was chosen because of a tight timeline and the simulation specialist working on this model was more familiar with the IES VE tool for building the 3d geometry.

**Solar Chimney to Enhance Natural Ventilation**

This project features the use of several tools to develop and refine the design. The building location is in a hot, sunny climate. Several wings of a building are connected by courtyards and wide passageways open to the outdoors at three entryway locations. Overhead, several skylights admit light through the roof. A suspended ceiling with a relatively high amount of perforated area resides below the roof.

The design intent is for air movement through the interconnected courtyards and passageways to improve occupant thermal comfort conditions. Air movement is induced into these areas by building air intake systems extracting air from the courtyards and by a large solar chimney drawing air from the courtyards. To create desirable spaces, aesthetic daylighting objectives were established and solar gains were reduced as much as possible.

To meet the desired daylighting aesthetics, which included introducing large amounts of visible lights to create dramatic contrast, yet reduce solar gains as much as possible, the international glazing database in Window5.2 was searched to select glazing products that would achieve these objectives by having high transmission of visible lights while using low-e coating on the #2 surface to reduce introduction of sun light outside the visible spectrum, particularly the infra-red range.

Next, a zonal thermal model with nodal air flow network was developed using IES VE. This model included zones for individual courtyards, passageways, adjacent conditioned building zones, ceiling plenums, and the solar chimney (represented by breaking the geometry up into several zones). Simulations were performed for a typical meteorological year. From these simulations, mean radiant and air temperatures were extracted for use with an in-house PMV/PPD spreadsheet calculator. The PMV/PPD calculator was developed to overcome a limitation in the calculations of mean radiant temperatures in IES VE for spaces which are modelled by more than one zone (the thermal model in IES VE sees a separation between two zones which is not a wall as a surface at a representative temperature, skewing the calculations of a mean radiant temperature in those zones) and in order to be able to assign different air speeds in the thermal comfort calculations for each hour of the year. These air speeds were derived from a combination of climate data and the CFD study described below.

CFD modelling was used extensively to predict air movement throughout the courtyards and passageways under a variety of outdoor wind speeds, directions and solar conditions. An interesting outcome of this work was the reduction in air movement that occurs at times in a central courtyard at the confluence with another passageway. These simulation results were used to provide predictions of interior wind speeds for use in the PMV/PPD spreadsheet calculator.

CFD modelling was also used to investigate air movement patterns and rates through the solar chimney. An example result is given in Figure 3. Various glazing options and design configurations were considered. As well, limiting conditions such as potential periods with backflow were investigated to develop proper controls and predict rates of possible occurrence. The CFD results were used to derive flow resistance values for the air flow nodal network model of the solar chimney in IES VE. The CFD results of final solar chimney design parameters compared reasonably well with air flow nodal network modelling results including the resistance values from the CFD results. This increased confidence in the thermal comfort analysis based on the thermal and air flow nodal network model in IES VE.

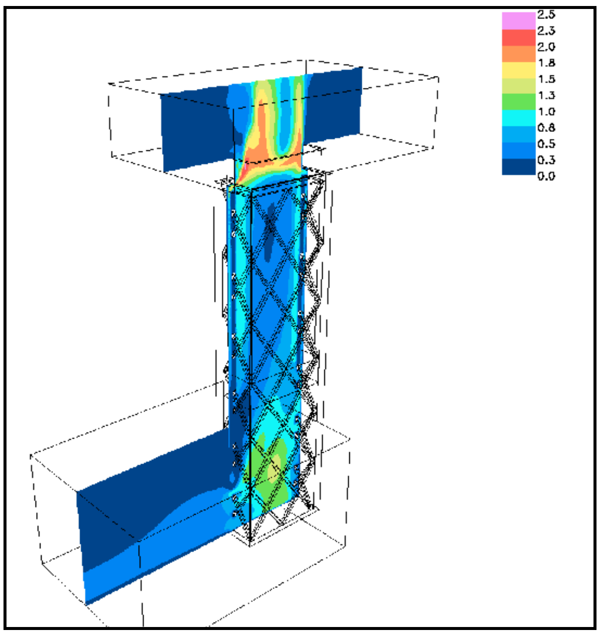


**Figure 3: Air flow velocities in a thermal chimney from CFD.**

Although the prediction of air flow through the building and subsequent thermal comfort predictions was the primary design concern investigated, another concern was the potential build-up of heat in the ceiling plenum, which could lead to discomfort due to radiative exchange with a resulting hot ceiling in the occupied space. IES VE simulation results showed air flow rates and temperature predictions that initially seemed counter-intuitive. Careful study of the predicted air movement patterns showed that the simulation was indeed calculating air flow rates and directions according to the embedded algorithms, but that these predictions were not necessarily accurate due to the exclusion of momentum and buoyancy-driven air movement in the model.

It was therefore decided to establish an upper bound for the ceiling plenum temperatures by analyzing the ceiling plenum further by blocking air flow paths to this space and simulating for a hot, sunny day. Predicted temperatures and heat transfer rates compared well with those calculated by using fundamental heat transfer calculations that were conducted as a check for the simulation results. These results demonstrated that plenum temperatures would not reach excessive levels and that in fact the roof insulation layer should be removed, since it was found that outside surface temperatures are typically below plenum air temperatures. Therefore insulation, instead of separating a cool space from a warm outside environment, is in fact more likely to inhibit a beneficial heat loss. The low exterior temperatures are the result of the choice of a highly reflective external roof surface.

This case study shows how designing for thermal and visual comfort achieved by passive measures can take a number of studies for one particular space. In this case glazing selection impacts visual performance and solar gains; these solar gains in combination with the natural ventilation pattern define the comfort conditions for a given climate. Window5.2 has been used for glazing selection, Ecotect and RADIANCE for visual comfort, and IES VE to calculate the yearly thermal performance of the space. These yearly calculations have the advantage of providing frequency information. The results show how often and for how long certain temperature ranges are exceeded. However, zonal thermal models coupled with airflow network models are limited in a number of ways. They do not resolve details in a space. Also, they do not calculate conservation of momentum, assuming that all momentum is dissipated within the zone. Buoyancy is not fully modelled either. These limitations are overcome by CFD calculations which show a great deal of detail, however, they are limited to either critical steady state situations or short transient calculations. The additional detail comes at the cost of much longer computational times. In order to execute thermal comfort simulations based on the IES VE results and the CFD results a in-house spreadsheet had to be developed for two reasons. Firstly, when calculating the comfort parameters in IES VE for a model that has zones connected by large openings, IES VE assigns a temperature to the walls with the large openings not taking into account the reduced area due to the opening. Secondly, the IES VE comfort calculator only allows for the input of one wind speed that is then applied to the thermal conditions throughout the year. However, in this naturally ventilated space the air speeds in the space depend on the weather and thus change hourly in the model as well as all other parameters. Lastly, as buoyancy generally is not properly modelled in airflow network models of the kind used in IES VE (the same is the case for Airnet coupled with EnergyPlus), special care was taken to evaluate temperatures in a ceiling plenum. Instead of taking input from architectural drawings directly and try to match the input fields provided by the software as closely as possible to the architectural drawings, a sensitivity analysis was performed on the predicted temperature under the roof and complemented with a simplified fundamental calculation. This combination provided good design guidance based on estimated temperatures for the plenum over the course of a typical year. In principle CFD simulations could have provided even more detail, however, this was deemed too much of an additional effort for this particular question, just to increase confidence with the estimate from the thermal simulation, which seemed sufficient for this particular question.

**Trombe Wall for Preheat of Ventilation Air and Passive Solar Heating**

Another example is a project in which the design team was keen to utilize a large Trombe wall for a proposed multi-unit residential building but was unsure how to design for peak performance. The building is situated in a sunny Canadian prairie climate. The schematic design called for a large 6-storey south-facing Trombe wall to encompass one façade of the building. The design intent is to use heated air created by the Trombe wall construction to supplement the building's air heating requirements in cold conditions and to drive airflow for naturally ventilating spaces during hot summer conditions (i.e act as a solar chimney). A second passive solar design idea was suggested for study: to situate a heavy mass interior wall on one side of a corridor with a highly glazed, southeast-facing exterior wall on the other side. In this case the space used for capturing solar heat is at the same time an occupied corridor. The intent of this proposed design is to store and transfer solar gains to the residential spaces on the other side of the heavy mass wall.

An IES VE zonal thermal model and air flow network model was developed to help assess the performance of the proposed designs. Parameters investigated included: glazing properties, Trombe wall thickness and material selections, and seasonal operation strategies. Simulation outputs used as performance metrics included temperatures and airflow rates generated in the gap and potential contribution to the building's annual heating and cooling loads.

Simulation results revealed that the design parameters of the Trombe wall could be adjusted to provide significant contributions to the building's heating loads. The results also revealed that, to meet these performance levels, the potential exists for overheating of zones on the back side of the Trombe wall. Some useful heat transfer to non-regularly occupied spaces (such as corridors) was observed, but the degree of overheating as a result of heat transfer from the large thermal mass to adjacent garbage, utility, and elevator shafts was unacceptable. The design team used this information to revisit floor plan layouts and thermal insulation strategies. Simulations also revealed that significant airflow rates were possible in the Trombe wall gap. The potential for driving natural cooling during hot summer periods was now a known quantity that was used by the design team to assist in determining the merit of the overall design.

It can be the case that poorly planned sustainable design measures are more of a hindrance to a building's energy efficiency than a benefit. For this reason, it is very important that well informed decisions are made early on in the design process. An example of this was seen on this project with the second proposed passive solar component, the corridor with an exterior glass wall and an interior wall high in thermal mass. Simulations revealed that zone temperatures in the corridors were too high to be comfortable for human occupation. Through parameter variation (glazing size and properties), solar gains and zone temperatures were reduced to an acceptable comfort level resulting in almost no benefit observed by increasing thermal mass to store and transfer heat to the spaces behind. The design was subsequently abandoned.

This case study shows that some design questions can in fact be answered by using one simulation tool only. In this case on zonal thermal model coupled with an airflow network model was used to evaluate the performance of this multi-residential building.

**Double Shell Roof**

For this office building in a temperate climate, the client desired a high level of daylight throughout the year. Another requirement was for the building to have a non-obtrusive, unassuming appearance. A two storey structure was envisioned to satisfy this requirement, but the resulting perimeter zone area relative to core zone area was quite low due to the substantial building space requirement.

To satisfy the desire for ample daylighting, a double shell roof was proposed that would be composed primarily of transparent and translucent components. The roof would have a slight incline, with openings for incoming ventilation or outgoing exhaust air on one side and connections to building systems on the other.

A conceptual design was developed that involved using the roof air cavity for ventilation preheat or routing building exhaust air through the cavity when cold outside, and either active or passive cooling with outdoor air when in cooling mode. The configuration is schematically shown in Figure 4. Roof cavity air would remain stagnant during unoccupied hours.

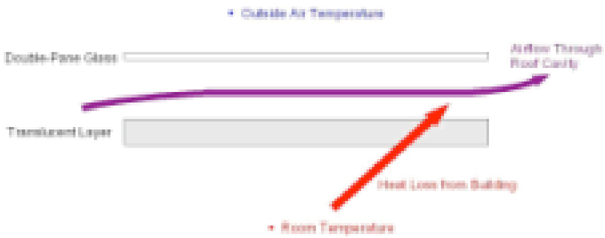


**Figure 4: Schematic of the double shell roof.**

An innovative, highly durable transparent roof glazing system was identified for the outer shell. Several material options were identified for the lower layer, each with different light transmissivity and thermal resistance values.

The critical questions to be answered for each option included:

1. How much daylight would be admitted into the building during overcast conditions (the predominant climate condition for this location)?
2. How would the roof perform thermally, especially when air moved through the cavity, taking into account any additional benefits (i.e. ventilation preheat)?

As a first step, the aesthetic appearance of the interior and illuminance levels under an overcast sky condition were investigated by developing the building geometry in IES VE, then exporting to RADIANCE.

The next step was to investigate the thermal effectiveness of each roof option for the various operating scenarios described above. For the stagnant cavity air case, a combination of hand calculations and Window5.2 results were initially used to estimate performance and to compare as a check with subsequent simulation results. For the three proposed operating scenarios under design winter conditions (ventilation preheat, exhausting or stagnant cavity air), computational fluid dynamics simulations were performed using FLUENT. An example result for the temperature distribution in the roof cavity is shown in Figure 5.

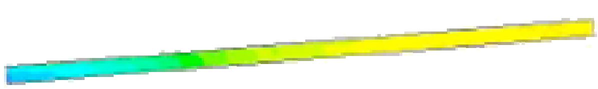

**Figure 5: Example temperature distribution in the double-shell roof cavity.**

Effective R-values were derived for these cases to be able to compare the roof performance with common solid roofs.

RADIANCE images demonstrated the potential for a highly desirable work space, with bright, diffuse light that is well distributed and no harsh contrasts from shadows through the use of translucent materials. The predicted illuminance levels also let the design team know what range of transmissivity values would be appropriate for the selected layers.

CFD simulation results compared well with hand calculations and Window5.2 results for roof thermal resistance estimates under stagnant air conditions. These results also demonstrated the added benefit of schemes involving ventilation preheat and routing building exhaust through the air cavity. Several material combinations where investigated in the different ventilation modes, allowing the design team to reduce the number of options to a few that would result in the desired low heating loads to the building. This allows for a design with introducing a high amount of daylight into the building, controlling solar loads in the summer through ventilating the shell and acceptable heating loads in the winter.

In this particular case the reason to use a combination of design tools results from firstly the need of a combination of high visual comfort and low heating loads, and secondly because the calculation principles that apply for the computation of effective insulation performance are very different when airflow through the envelop structure is involved. When air flows through the roof the effective resistance to heat loss, including heat loss to or gain from the air flow needed to be calculated with CFD. When there is no airflow, a CFD calculation without inflow or outflow of air can be performed as well, however, now the opportunity exists to use a tool that is much more sophisticated to calculate the performance of glazing combinations, Window5.2. Because it is limited with respect to including air flows, it cannot be used for the cases with air flow. To increase confidence in the results, the result of a CFD calculation without air flowing through and the Window5.2 results were compared. They compared well.

## CONCLUSIONS

In the present paper a number of examples of the design of passive building features have been given. For each example the design challenge(s) faced by the design team were described. It was than explained how crucial information for design decisions is provided by simulations of the performance of the passive design options with respect to thermal comfort and energy consumption. Often more than one software tool as well as fundamental heat and mass transfer calculations are needed to answer the questions to a satisfying degree of information. There is not one software product yet that combines all necessary calculations, and with the level of control that is needed. Instead, a number of tools needs to be used to address all aspects of a design. It was also described how it can be important to be aware of the simulation model limitations, such as for example in the case of estimating the ceiling plenum temperatures. If one would not have known that the ventilation of the plenum was not calculated properly without taking momentum conservation into account, the use of the nodal air flow model in this case could have lead to an underprediction of plenum temperatures. It is important to be aware of the limitations of the different models, and this will remain important independent of progress in simulation software. It is necessary that the results of simulations are performed and reviewed by qualified personnel to avoid accidentally using inappropriate models.

The questions arising in the decision process include both, critical design conditions, that often need very detailed and accurate simulation models, such, and questions about the overall performance over the course of a typical year. As an example, CFD provides a lot of detail for critical design decisions. In order to be able to calculate a whole year the simulation model has to be simplified compared to CFD, as the calculation times of CFD are prohibitive for such an application. Here, nodal air flow models are more suitable. Concluding, the integration of engineering studies into the design process calls for the use of a range of different software tools while being aware of their strengths and limitations.

Particularly in an integrated design setting, simulations become a communication tool. Design teams can see the impact of a design option on a design's performance, and can compare the relative impacts of a number of different design options. This is typically combined with a cost analysis so that a potential benefit can be directly compared to the necessary investments. In this paper examples are given for both processes where the simulations helped moving ambitious designs forward to achieve design goals, as well as simulations that helped the design team to understand the implications of a particular concept leading to a re-orientation toward other options. Both situations show how simulations and simulation tools provide clarity to the decision process of the design team and enable the team to focus early on appropriate concepts.

## REFERENCES


Afonso C., Oliveira A. (2000), 'Solar chimneys: simulation and experiment', *Energy and Buildings*, 32 (1) 71-79.

Miyazaki T., Akisawa A., Kashiwagi T. (2006), 'The effects of solar chimneys on thermal load mitigation of office buildings under the Japanese climate', *Renewable Energy*, 31 (7) 987-1010.

Gan G.H. (2006), 'Simulation of buoyancy-induced flow in open cavities for natural ventilation, *Energy and Buildings*, 38 (5) 410-420.

Macias M., Mateo A., Schuler M., Mitre E.M. (2006), 'Application of night cooling concept to social housing design in dry hot climate', *Energy and Buildings*, 38 (9) 1104-1110.

Jle J., Hua Y., Wei H., Gang P., Lu J.P., Bin J., (2007), 'Modeling of a novel Trombe wall with PV cells', *Building and Environment*, 42 (3) 1544-1552.

Burek S.A.M., Habeb A. (2007), 'Air flow and thermal efficiency characteristics in solar chimneys and Trombe Walls', *Energy and Buildings*, 39 (2) 128-135.

Shen J.B., Lassue S., Zalewski L., Huang, D.Z. (2007), 'Numerical study on thermal behavior of classical or composite Trombe solar walls', *Energy and Buildings*, 39 (8) 962-974.

Bacharoudis E., Vrachopoulos M.G., Koukou M.K., Margaris D., Filios A.E., Mavrommatis S.A. (2007), 'Study of the natural convection phenomena inside a wall solar chimney with one wall adiabatic and one wall under a heat flux', *Applied Thermal Engineering*, 26 (13) 2266-2275.

Ecotect by SQUARE ONE research, http://www.squ1.com/products/ecotect, sourced 10 March 2008

RADIANCE, http://radsite.lbl.gov/RADIANCE/, sourced 10 March 2008

Ward Larson, G., Shakespeare, R., *Rendering with RADIANCE*, Morgan Kaufmann, 1998

Reinhard, C. et al, *Daysim*, http://irc.nrc-cnrc.gc.ca/ie/lighting/daylight/daysim_e.html, sourced 10 March 2008

Window5.2, http://windows.lbl.gov/software/window/window.html, sourced 10 March 2008

Virtual Environment by IES, http://iesve.com, sourced 10 March 2008

EnergyPlus, http://www.eere.energy.gov/buildings/energyplus/, sourced 10 March 2008

FLUENT, http://www.fluent.com, sourced 10 March 2008