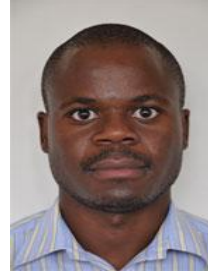


PREDICTIVE PERFORMANCE SIMULATIONS FOR A SUSTAINABLE LECTURE BUILDING COMPLEX



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Summary

During the course of 2009 and 2010 the building performance laboratory (BPL) of South Africa's Council for Scientific and Industrial Research (CSIR) undertook predictive simulations to quantify the expected performance of an advanced new lecture and office building complex for the East London campus of the University of Fort Hare. The design of the building is both unique and complex, combining wind-driven technologies (an aerofoil) and solar-driven technologies (a Trombe wall) to drive a substantially passive ventilation process. The aim of this research was to generate a useable and useful appraisal of the building's likely performance, under various conditions, and to provide an indication of the approximate frequency of those conditions during operational hours. The following process was used to model the ventilation performance of this mixed-mode building.

1. An insolation analysis was undertaken to establish the effect of cumulative exposure of the Trombe wall surface to solar radiation. Moment-in-time radiation reports were generated using *Ecotect*TM software for the building. The data were used as input for the internal analysis.
2. The available wind speed and direction data were verified and their prevalence estimated. Five representative wind speeds and five directions were analysed and used as input data for an external wind study.
3. An external surrounding urban air movement study, using computational fluid dynamics (CFD) software, was undertaken to determine external boundary conditions from an extensive section of the urban landscape. This was used as input data for a detailed interior combined thermal and air-movement analysis.
4. An internal combined thermal and wind analysis was undertaken to estimate the combined effect on ventilation rates of combined wind-driven technologies and solar-driven technologies.
5. A study of an alternative aerofoil shape was undertaken to provide design decision-support.
6. After completion, the team undertook initial measurements to establish the accuracy of the predictive simulations. This is an ongoing process and it will take a long time before the actual performance is fully quantified. The turbulent airflow of the urban environment causes low air speeds reaching the building. This affects the venturi negatively. Interior spaces are predicted to have variable air changes, which are condition dependent. The aerofoil and Trombe operate well in combination for most combinations of direction and wind speed. Depending on prevailing weather conditions, the venturi and Trombe contribute to ventilation in different proportions. In certain conditions the two systems tend to undermine each other's efficiency.

Keywords: predictive simulation, computational fluid dynamics, Trombe, aerofoil, venturi

1. Introduction

The CSIR was commissioned by the consulting engineers of the project to participate in the development of a new lecture and office building complex for the East London campus of the University of Fort Hare (UFH). The CSIR team used its building performance modelling technology to test design solutions prepared by the design team (Native Architects and others).

A key objective of the design team was to develop a design that would have a minimal ecological footprint through the construction and operational phases of the building life-cycle. To achieve this, the building design was conceptualised as a fully naturally ventilated building. Various experimental technologies were incorporated in the building design to achieve an efficient building that will provide comfortable conditions for all users throughout the year, without dependence on mechanical ventilation systems. The tasks of the CSIR (simulation team) were:

- To analyse the anticipated performance of the proposed naturally ventilated building design by means of advanced virtual software simulation techniques;
- To provide feedback to the design team;
- Where appropriate, to make minor adjustments to design proposals of the design team in pursuit of improvement of the performance.

This project is unique as a Trombe is used to drive ventilation by means of buoyancy and a venturi to use air movement to create suction at an exit slot on the roof. The classical Trombe wall is a massive wall that is covered by exterior glazing with an air channel in between, used primarily to heat and cool the building (Chan et al., 2010).

The fundamental purpose of the Trombe (solar chimney) in this project is to generate airflow through a building by converting thermal energy into kinetic energy of air movement (Chan et al., 2010). In this project, air in the Trombe is heated by means of solar radiation-heated semi-circular pre-cast concrete panels that are painted matt black to increase efficiency. As the hot air rises in the Trombe slot, it draws in fresh air from the southern side of the building into hollow floors. These hollow floors have well-distributed floor outlets that ventilate the lecture spaces. At the top of the northern wall of the lecture rooms are high-level exhaust slots where the air escapes into the Trombe. It rises in the Trombe and exits at the top of the roof in a venturi slot (Figure 5). Some researchers would classify the application in this project as a solar chimney.

2. The process

Figure 1 gives an overview of the various building performance analysis processes followed to predict the building's performance.

2.1 Climate analysis

The coastal city East London has a Köppen-Geiger Cfa classification type climate (Kottek et al., 2006). This climate is a warm temperate, fully humid with hot summers. The site is located some 200 m from the East London harbour on a southern slope within an old two to three-storey cityscape.

The original wind data for 2007 of the South African Weather Service (SAWS), that were provided by the consulting engineer, were integrated into a standard *Ecotect*[™] weather file to ensure maximum accuracy. Some differences in the direction and strength of the predominant wind were noticed when the latest weather file was compared with the original *Ecotect*[™] East London weather file used during the course of 2009. To cross-check the wind information further, the wind output from a mobile Davis weather station and the latest reworked weather file were compared in a spreadsheet. A good correlation was noticed and it appeared that the SAWS data were reliable for building performance analysis purposes.

Subsequently, various other analyses and studies were undertaken. The first one is a detailed wind speed analysis that indicates how many hours the wind blows at a particular strength within the operational hours of the building, i.e. 07:00 to 21:00.

An analysis was made of the number of hours and at what strength the wind blows in 10° direction intervals. The detailed external-internal CFD analyses quantified the directional performance of the building. It is interesting to see how the building performs with different wind directions, especially when the Trombe contributes to the ventilation rate. A spreadsheet has been prepared with various tabs and small graphs that indicate how many hours and at what strength the wind blows in the direction indicated on the spreadsheet tab.

2.1 Insolation analysis: How much radiation reaches Trombe?

The climate analysis on its own is not adequate to understand and quantify the distribution of radiation on the façade of the building. In literature, many approaches can be found to evaluate the shape of shadows cast on a window. Finite analyses and radiosity methods tend to be time-consuming, while trigonometric procedures are limited to a few simple geometries (Cascone et al., 2011). To address this, a set of 27 insolation graphs were created in *Ecotect*TM using ray-tracing.

'Insolation' refers to an 'incident solar radiation' analysis and represents the amount of cumulative incident radiation on a point or surface over a specified period. First overshadowing masks are generated at each point to take account of surrounding buildings and objects and then hourly diffuse and direct radiation data are read directly from the climate data over a user-defined period.

The analysis grid-size was set to correspond vertically to the UFH floor height and horizontally approximately a 8 400 mm module. In all cases the analyses were done for the morning 08:30 to

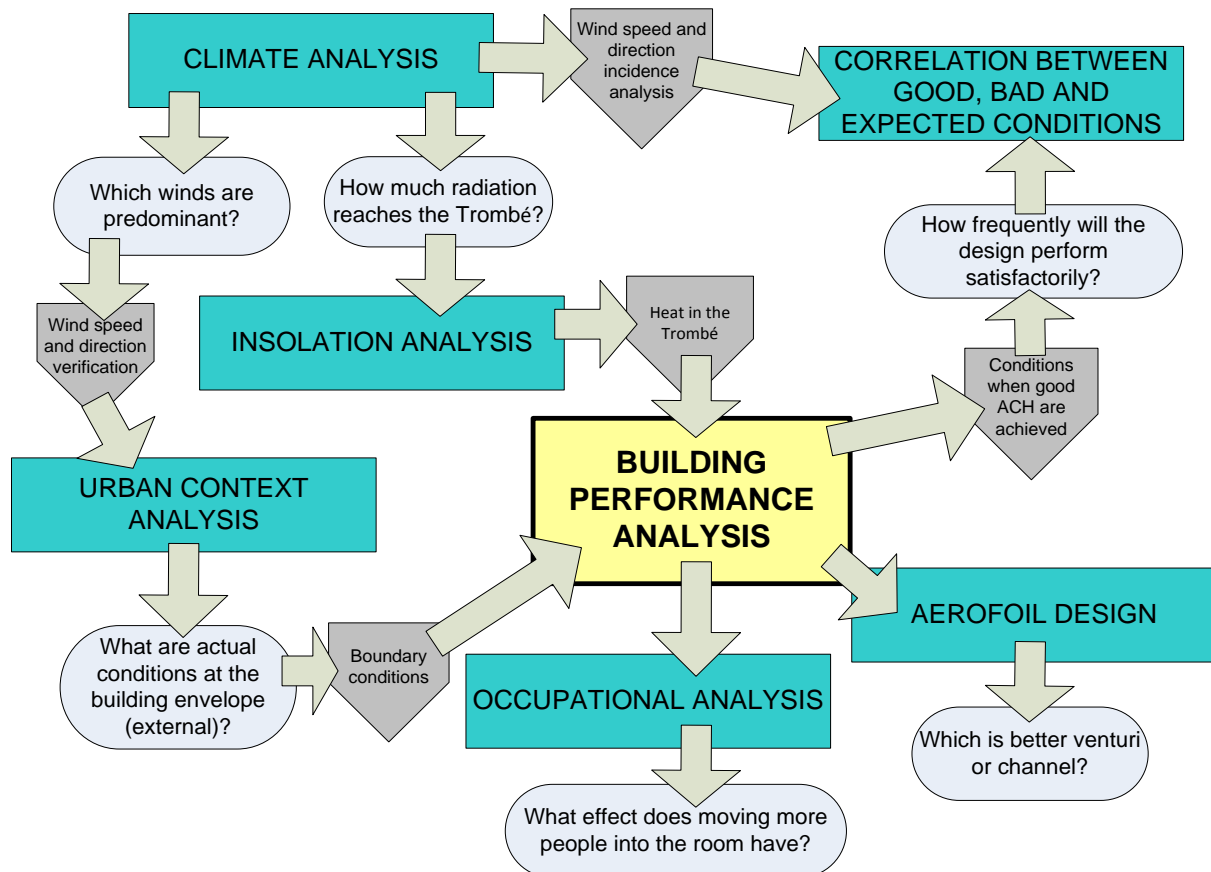


Figure 1 The building performance analysis process

09:h30, midday from 11:30 to 12:30 and the afternoon 14:30 to 15h:00 for Summer and Winter Solstices and the Vernal Equinox. From a radiation point of view the vernal and autumnal equinoxes are equivalent, as the solar angles are identical. The radiation levels that were used are 0 W/m², 500 W/m² and 1 000 W/m² direct radiation. Even with 0 W/m² direct radiation there is still a significant amount of indirect (diffuse) radiation available - as much as 200 W/m². The results are expressed in *Wh*. As expected, it was noticed that clouds have a significant effect, especially on direct radiation. See Figure 2 for examples of the various insolation results. Please note that the same colour in the various graphs do not always indicate the same level of radiation (Figure 2). In all cases, one should refer to the legend in the top right-hand corner. The buildings are displayed in "wireframe" mode so that the entire analysis surface can be seen. The general lack of radiation in the walkway areas connecting the various building blocks is noticeable due to the significant overshadowing at certain times.

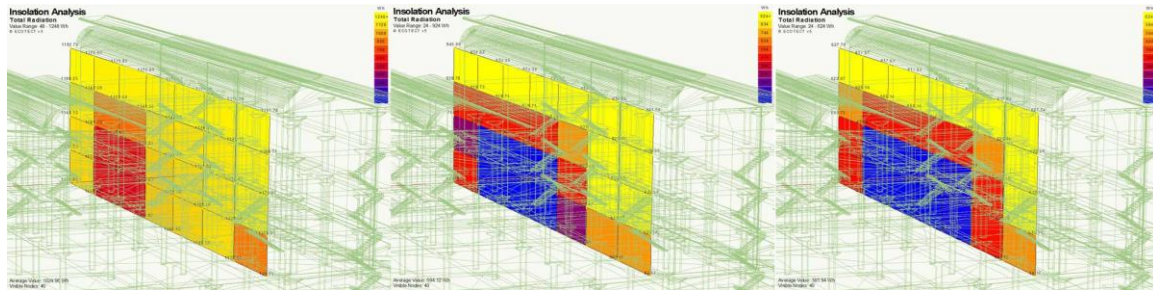


Figure 2 Insolation analysis 11:30 to 12h:00 for Summer Solstice (21 December), Vernal Equinox (23 September) and Winter Solstice (21 June)

2.1.1 Incident radiation

Insolation refers only to the amount of energy actually falling on a surface, which is not affected in any way by the surface properties of materials or by any internal refractive effects. Material properties only affect the amount of solar radiation absorbed and/or transmitted by a surface. Insolation ($E_{incident}$) is therefore affected only by the angle of incidence of the radiation (A), the fraction of the surface currently in shadow from other surrounding geometry (F_{shad}), the fraction of the diffuse sky actually visible from the surface (F_{sky}) and, if a surface is partially adjacent to another zone, the area of surface actually exposed to solar radiation (A_{ex}). These factors affect the beam normal (E_{beam}) and diffuse sky ($E_{diffuse}$) radiation differently, such that:

$$E_{incident} = \left[\left(E_{beam} \times \cos(A) \times F_{shad} \right) + \left(E_{diffuse} \times F_{sky} \right) \right] \times A_{ex} \quad (1)$$

2.1.2 Angle of incidence

When radiation from the Sun strikes the surface of an object from directly front-on, the energy density per unit-area will be much higher than if the radiation struck from a much greater angle. This effect can be calculated using the cosine law, where the radiant energy from the Sun is multiplied by the cosine of the incidence angle. The incidence angle is always calculated relative to the surface normal of each plane. Radiant energy density is at its maximum at normal incidence when the incidence angle approaches zero. It is at its minimum at grazing incidence when the incidence angle approaches 90°. For example, when the radiation strikes at 75°, it imparts only 26% of its energy to the surface. At 15°, it imparts 96% of its energy. At 0° it would impart 100% and at 90° it would impart 0%, as it no longer actually strikes the surface.

2.2 Urban context analysis



Figure 3 Wind directions used in the CFD analysis

An extensive, detailed and time-consuming range of CFD analyses using STAR CCM+ and Ansys Airpak has been undertaken to understand (quantify) the building performance. The CFD analyses were undertaken in two phases. Due to the complexity of the model, exterior studies (urban

environment) were first done for 0°, 50°, 90°, 140° and 180° with respect to the building (Figure 3). In each case, wind speeds for 1.5, 2.5, 3.5, 4.5 and 5.5 m/s were used (a total of 25 permutations). These established the boundary conditions for the detailed building performance analysis mentioned below. A CFD image of the outside urban environment is included as an example of the urban context analysis. As many surrounding buildings as possible have been included in the CFD analysis to get a good idea of the effect of the turbulent airflow and ground effect on the UFH building.

To illustrate the level of detail in the external model as well as the number of buildings, two figures have been included. The left of Figure 4 illustrates the movement of a wind of 5.5 m/s (direction 0°) over the turbulent urban environment and the right of Figure 4 shows the pressure differences over the same area.

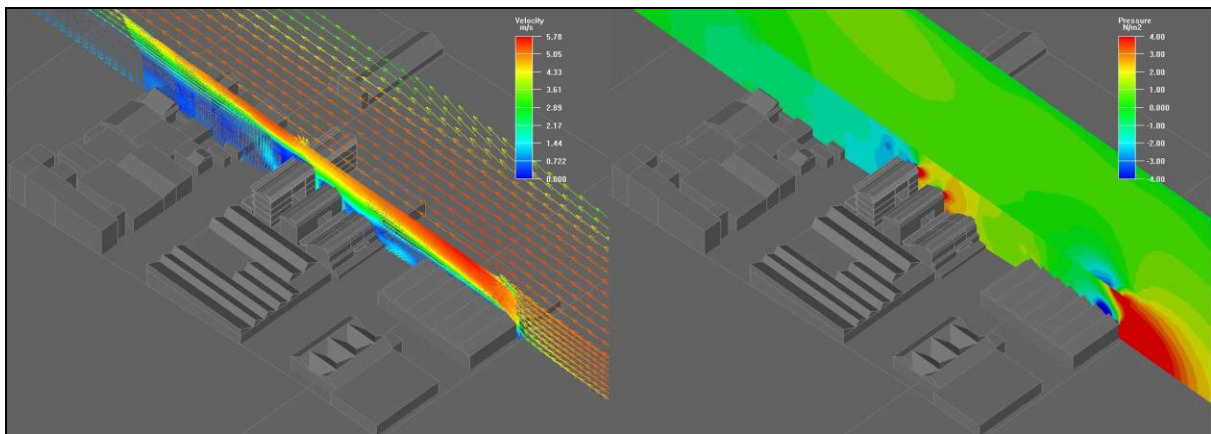


Figure 4 An urban study with a 5.5 m/s wind from direction 0°(Figure 3). The image on the left shows the velocity profile and the one on the right the pressure distribution in Pa (N/m²).

2.3 Interior building performance analysis

A total of 274 CFD simulations using ANSYS Airpak was run for a detailed section of the southern block to characterise the ventilation rate with different wind directions/strength and different solar radiation levels. Due to the time-consuming nature of the simulations, only wind velocities of 1.5 and 5.5 m/s were simulated for the wind directions illustrated in Figure 3.

When the predicted results were analysed, interesting performance characteristics were observed. With direction 0° and a wind speed of 1.5 m/s, the ventilation was mostly Trombe-driven with 11.28 air changes per hour (ACH) for floor 1. For the same wind direction and a wind of 5.5 m/s, most of the ventilation was contributed by the venturi and the ventilation reached a maximum of 6.9 ACH.

For a wind direction of 50°, the Trombe dominates at both 1.5 and 5.5 m/s wind speeds. The ventilation rate reaches a value 12.78 ACH and 12.22 ACH, respectively, in these cases for floor 1.

At a wind angle of 90°, the Trombe continues to dominate because the wind hits the side of the building. The ventilation rate for a 1.5 m/s wind reaches a maximum of 12.83 ACH and for a 5.5 m/s wind, 11.12 ACH.

In all the Trombe-dominated situations the bottom floors always have better ventilation (ACH) than the top floors due to the characteristics of buoyancy-driven airflow (CIBSE, 1997). The Trombe was generally more efficient than the venturi, in above-mentioned cases, because the venturi is compromised with the building orientation and the turbulent air flow that reaches it over the urban environment.

At a wind angle of 140° and a wind speed of 1.5 m/s, the Trombe dominates giving a maximum of 12.96 ACH for floor 1. For a wind speed of 5.5 m/s, the Trombe still contributes quite a lot, but it is apparent that the wind pressure from the southern side blowing directly into the hollow floor also contributes. In this case 13.49 ACH is reached.

At a wind angle of 180° and a wind speed of 1.5 m/s, the Trombe contributes, but less than with angle 140°, producing 12.92 ACH. With a wind speed of 5.5 m/s, it is clear that the wind pressure from the south into the hollow floor and possibly the venturi is predominantly driving the ventilation with the Trombe contributing virtually nothing. In this case a very good ACH of 13.03 is reached on floor 4.

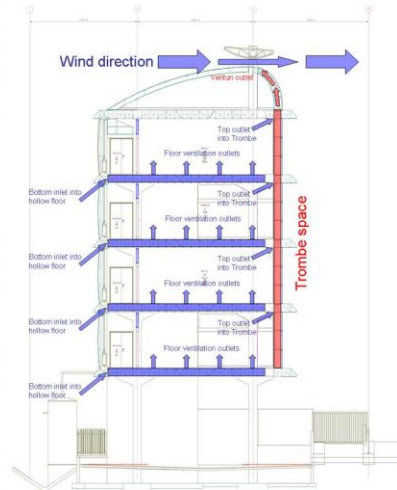


Figure 5 Completed building (left) and a typical section through the building (right) that illustrates the principles of the natural ventilation system used

3. Initial verification of predictive results (field measurements)

A set of field measurements was undertaken after completion of the building to determine the accuracy of the predictive simulations. The CSIR team visited the building on 25 August 2011 in East London to determine how well the actual performance compares with the predicted performance. The measurements were undertaken using the same detailed vertical section of the building that was predictively simulated before (Figure 6). A mobile Sentry hot wire ST732 anemometer was used to measure the ventilation effectiveness and temperature of various parts of the Trombe and the indoor space at the positions indicated in Figure 7. The blue dots indicate airspeed in m/s and the red dots temperature measurements in °C. The most important point with regard to air speed is the top ventilation outlet indicated with large blue circles (Figure 7). The top outlet was used because all air leaves the space through these slots (Figure 5) and the team realised that it would be the most accurate method.

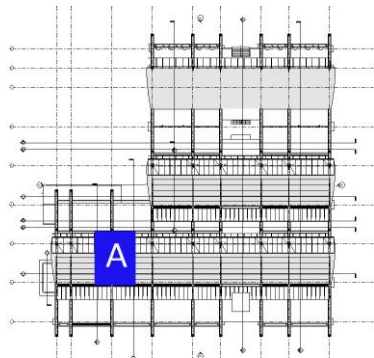


Figure 6 Area “A” indicates the position of the detailed predictive simulations

Figure 6 indicates three blocks in the building. Only the northern and southern blocks have actually been built. The implication of this change in the original brief is that the configuration for the predictive and measured performance is not identical, because the amount of isolation and wind characteristics are different. According to The Engineering Toolbox (2012) and ASHRAE (2005), for a given room, the supply air volume $Q(m^3/s)$ is

$$Q = Av \tag{2}$$

$$ACH = \frac{3600Q}{V} \tag{3}$$

where

- V is the volume of room (m^3)
- Q is the volume flow rate (m^3/s)
- A is the area of opening (m^2)
- v is the opening air velocity (m/s)
- ACH is the air changes per hour

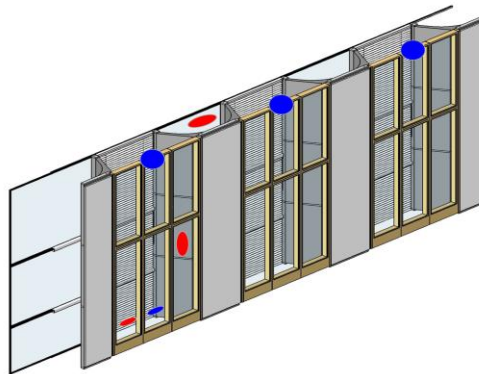


Figure 7 A section of the UFH Trombe that illustrates where measurements were taken. Red dots indicate temperature and blue dots airflow (m/s) measurements.

Summer Solstice 5.5 m/s (Direction 50)

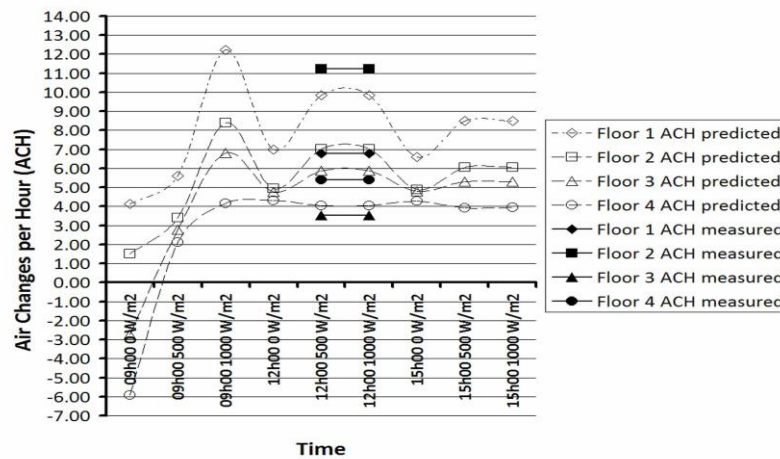


Figure 8 Predicted and measured air changes per hour for the direction 50°

The method mentioned was used to calculate the ACH. Upon arrival, CSIR researchers established that the wind was blowing from the north-east at 4.72 m/s. This corresponds closely with wind direction 50° used during simulation (Figure 3). The time of day and year corresponded closest with their predictive simulation for a 5.5 m/s, between 500 and 1 000 W/m^2 and Vernal Equinox. Inspection of their predicted and actual values showed that these do not correlate well. The researchers realised that because the middle block of the complex has not been built, more solar radiation and wind would actually reach the southern block. They also realised that the conditions for the Summer Solstice simulations are actually closer to the measured values. Figure 8 illustrates the simulated values for 09:00, 12:00 and 15:00 with direct solar radiation values of 0 W/m^2 , 500 W/m^2 and 1 000 W/m^2 . The actual radiation during measurement was estimated to be between 500 and 1 000 W/m^2 . The actual measured values are superimposed on the same graph (Figure 8). It is interesting to note that there are also negative ACH values. In the context of the graph this means that the air flow reverses. The graph indicates that this could possibly happen on floors 3 and 4 with low radiation and a wind of 5.5 m/s from

direction 50°. This is highly undesirable, because hot Trombe air would reverse flow into the teaching space, making it uncomfortable. However it is very unlikely to happen and has not yet been observed in the actual building after a number of months' operation.

3.1 SWOT analysis

The predictive simulations were invaluable in giving a degree of comfort to the client and design team as to the theoretical performance of the building. The main weakness is still that it is almost impossible to quantify the exact building performance due to the complex interactions of wind and sun. At this stage far too few in-situ measurements have been taken to form a complete picture of the actual building performance, however measurements are continuing. As theoretical knowledge of this type of simulation grows, the accuracy of predictive simulations will improve. A big threat in South Africa is the high cost of these simulations and the limited number of professionals who are able to undertake such simulations.

4. Conclusions

While it was very challenging to predict the performance of the building, the simulation team could prove that the building should theoretically perform well. The building is now in operation for a number of months and the experience is that it is performing well, even though the site and building are not ideally oriented regarding the prevailing wind directions that generally follow the coast. From the perspective of the design team, the commitment to use a building information management (BIM) system at inception needed a far more integrated approach to design development. Engineers typically wait for the architects to design the whole building, and then only drill down to final calculated structural design configurations and sizes. With BIM, these activities should be done in parallel so that the digital building model is built together. When the project was undertaken, CFD did not integrate with BIM at all. From a technical point of view, the following predictions have been qualitatively observed in operation:

- The spaces appear to have sufficient air changes, however the predictions indicated that there might be times when it will be inadequate or even having reverse airflows (Figure 8).
- With southerly and south-westerly winds, wind-driven ventilation is more prominent than Trombe or venturi-driven ventilation at low speed and totally dominates at higher wind speeds.
- All floors respond very differently to the different simulated conditions, with the floor 4 consistently performing weakly.
- Under Trombe-driven conditions, the upper floors generally have inadequate ACH (characteristic of buoyancy-driven air flow). Under the conditions measured (Figure 8), 11 ACH were achieved.
- The aerofoil and Trombe spaces operate well in combination for most direction and wind speed combinations. Under certain conditions the two systems undermine each other's efficiency, but it is not necessarily a problem.
- The measured values are better than the predicted values. This is, inter alia, due to the fact that the middle block has not been built and thus more radiation and wind reach the passive ventilation mechanisms.

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