A COMPARISON OF PREDICTED DESIGN EFFICACY AND ENVIRONMENTAL ASSESSMENT FOR TUBERCULOSIS CARE FACILITIES IN SOUTH AFRICA

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Abstract

The impact of Tuberculosis (TB) is of epidemic proportions in South Africa (SA) being one of the developing countries. Furthermore, studies seem to indicate that health care facilities are contributing to the spread of Mtb (Eshun-Wilson et al. 2008). The contribution that the built environment has on airborne transmission, combined with erratic energy supply and the international sustainable agenda raised the need for research investigation for passive design building response for airborne contagion.

Natural ventilation uses buoyancy or wind as the driving forces for air movement. In this paper Computational Fluid Dynamics (CFD) models were used to find out the optimum design for naturally ventilated Tuberculosis (TB) ward designs. Natural ventilation can reduce the concentration of airborne pathogens through removing and diluting airborne droplet nuclei. The effect of different parameters such as roof angle, window type and size, positioning of closures in the permanent ridge ventilators on natural ventilation performance were studied. The results indicated that the correct combination of the parameters mentioned can significantly improve the natural ventilation effectiveness.

Tracer gas tests using carbon dioxide (CO2) were subsequently conducted for the real spaces with natural ventilation systems as designed using CFD to establish the actual ventilation rates achieved. The ventilation rates results indicate generally good to excellent ventilation rates especially in the coastal regions. These rates are in line with the recommended rates as per the World Health Organisation (WHO) and Centres for Disease Control (CDC).

A Post Occupational Evaluation (POE) was undertaken through qualitative questionnaire and site assessment to evaluate the impact and potential success of the as built modelled design. It is evident though the various staff interviews and project team discussions that the new facilities have improved nursing standards and patient ward standards.

1. Introduction

The obligate aerobe nature of Mtb transmitted by airborne, impacts environments with an immune deficiency disease i.e. HIV, unsuspected patients, healthcare workers and healthy people at risk of contagion, with the emphasis on immunosuppressed persons. In 2008 the World Health Organisation (WHO) ranked South Africa (SA) as the worst infected country in the world (per capita) for Mtb. A WHO assessment in 2008 indicated the epidemiological burden of TB and HIV co-infection in SA at an estimated 70%. WHO estimates that in SA, out of every 100 000 people approximately 768 are Mtb positive and 5.5 million people in SA have HIV Aids. These facts point to alarming risk exposure in hospital environments.

The airborne nature for the spreading of TB makes TB disease difficult to control in health care facilities. The WHO and CDC identifies sufficient ventilation as one of the ways for controlling the spread of TB in health care facilities. Ventilation can reduce the concentration of airborne pathogens through removing and diluting airborne droplet nuclei (WHO, 2009 pp. 19). Ventilation in this paper is defined as the introduction of “fresh” air from a “safe” source (preferably outdoor air) to continually replenish indoor air. There are three strategies for ventilation namely natural ventilation, mixed mode ventilation and mechanical ventilation. Examples of natural ventilation strategies are windows, doors, turbine ventilators, door grills etc. Mixed mode ventilation strategy refers to mechanically assisted natural ventilation strategies e.g. motorised turbine ventilator. Mechanical ventilation system uses electric fans to drive airflow through a building. There are many advantages to reliance on natural ventilation for infection control such as low cost of installation, operation and maintenance which reduces the reliance on electricity supply, which is erratic and constrained in many certain areas, especially deep rural areas of South Africa.

This paper reports on natural ventilation systems design using CFD and results of field tests and experiments on ventilation rates achieved by the real spaces with natural ventilation systems as designed using CFD.

This paper discuses a recent research investigation conducted by the CSIR for the design and commissioning of TB care facilities in South Africa in considering natural ventilation as a viable sustainable design solution for airborne contamination control using contaminate dilution. A recent Global Fund M(X) DR-TB Infrastructure Project initiated by the SA National TB Control Programme aimed to provide 312 additional M(X) DR-TB beds for long-term inpatient care at eight hospitals in seven provinces (Nice *et al.*, 2012). This project presented the opportunity to investigate modelling design methodologies to present a design by research based outcome. Furthermore the project contributed to developing and consolidate guidelines for accommodating long-term patients within the broad policy framework developed by the National TB Control Programme at the time, subsequently focused has shifted to home based care.

Facilities ranged from DR-TB and MDR units, to dedicated MDR & XDR units, dependant of disease catchment areas and disease profile. To effectively address the public health crisis at the time (2008), the National Department of Health (NDoH) determined that all confirmed XDR and MDR-TB patients are to be hospitalised at specialised M(X)DR-TB units for the primary treatment period (usually 6-18 months). Existing long-term care facilities for the treatment of TB patients are, however, poorly designed to address needs of MDR and XDR-TB patients and of healthcare workers. Paving the way for new facilities which could reduce the risk of cross infection to patients and staff and create a more conducive healing environment.

The project required developing a research methodology based on key design principles that would on completion be measured by both quantitative means (CO_2 decay) or qualitatively (by questionnaires and other). One of the driving design principles was utilising natural ventilation as far as possible in all patient areas to achieve maximum air changes at all times. The target was set at 12 – 16 air changes per hour (ACH) as per the CDC and WHO recommendation at the time (this has evolved to include occupancy and now measured by L/p/s). There are many advantages to reliance on natural ventilation for infection control such as the low cost of installation, operation and maintenance which reduces the reliance on electricity supply, which is erratic and constrained in many certain areas, especially deep rural areas in South Africa.

Due to the many factors affecting natural ventilation as a design solution, it must be considered during the early stages of a facility's design development. Retro fitment is not ideal and could be very costly, with suboptimal performance. When developing the design concept for a naturally ventilated building the following basic steps must be considered (Parsons et al., 2010):

- "The desired airflow patterns from inlets to outlets through the occupied spaces need to be defined. This is related to the particular climatic region, site configuration, form and organisation of the building as well as the use patterns. All openings such as through windows, roof ventilators and other ventilators need to be considered."
- "Ventilation systems need to be omnidirectional as wind is highly variable in direction and strength and it is almost impossible to quantify it precisely."
- "The principle driving forces, which enable the desired airflow pattern and air changes, are to be identified. In good design the dominating driving forces are in sympathy with the intended flow rate and distribution."
- "The size, type and location of the openings such as windows so that the required flow rates can be delivered under all operating conditions."

It was clear from abovementioned that there are really only two ways that the airflows could be quantified, i.e. in a low speed wind tunnel or by means of Computational Fluid Dynamics (CFD). In order to provide technical assistance to design teams, the CSIR Building Performance Laboratory[1] provided decision support for natural ventilation design.

The proverbial 'proof of the pudding is in the eating' was carefully considered. The opportunity to test the various design decision iterations established by CFD modelling results could be implemented in built form. This afforded the opportunity to physically, by experimentation, test the efficacy of the elected design solutions two years post occupation of the facilities. The assessment technique selected for this assessment was the CO_2 decay technique, tested under various site conditions. Combined with a qualitative POE questionnaire and program assessment gave the design team insight into the efficacy of the suggested solutions, the success in the proposed methodology and the user experience.

2. Research Background

This paper presents the process of developing a design methodology that can be used in the design for natural ventilation buildings; firstly that incorporates CFD modelling to inform design planning and secondly conduct performance analysis through site experiments to test the 'real world' performance. When considering the project objective: 'to reduce the burden of tuberculosis and HIV in South Africa' a built environment approach was conceived: built environment intervention through design measures that could potentially advance the development of effective airborne infection control by natural ventilation, and lead to

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[1] The Building Performance Laboratory is a specialized focus area located in the Building Science and Technology research programme at the CSIR which uses predictive modelling of building performance towards achieving environmentally, functionally and operationally appropriate and affordable design solutions for the built environment.

the development of Norms and standards for TB facilities not only in and for South Africa, but also other infected parts of the world. We consider the three part methodology:

1) Computational Fluid Dynamics (CFD)
2) Ventilation performance indicators – review of techniques and final selection
3) The Post Occupancy evaluation

2.1 Computational Fluid Dynamics (CFD)

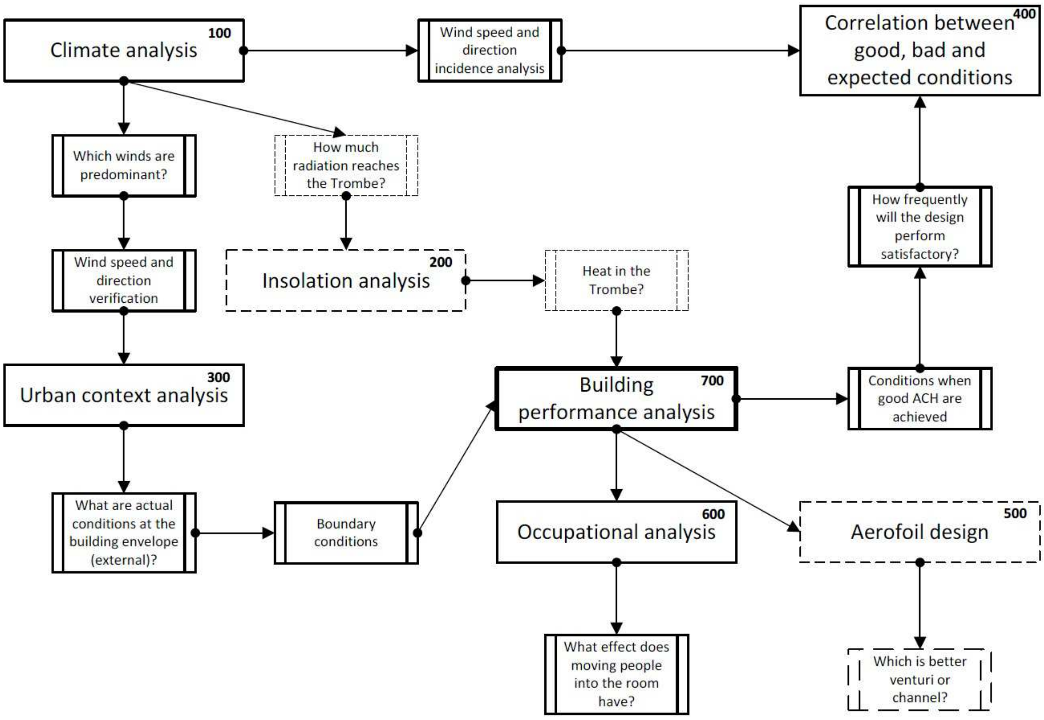

Figure 1 Methodology followed to simulate ventilation performance.

CFD simulations in the built environment are complex, because the external airflows are highly turbulent due to the interference of different structures and a significant amount of ground effect. Furthermore the accurate quantification of climatic conditions such as wind direction and strength, temperature and humidity is extremely difficult. In this project CFD was used both as a qualitative and quantitative tool. The former was used to experiment with different roof monitor configurations and the latter to determine the actual ventilation effectiveness. At the time when the research was undertaken the team had little prior experience of CFD. An *Ansys Airpak* CFD package was acquired to undertake the CFD analysis, because it was easier to master than *Ansys Fluent*. The methodology that was adopted in the CFD modelling was essentially a two-stage approach (Figure 1) where an external CFD site model was first created to study external airflows and to determine the boundary conditions for a detailed zoom-in model to determine the ventilation performance. The former contained block models of all the buildings on the site as accurately as possible whilst the latter contained all the detailed building detail such as walls, windows, roof and roof ventilators. In the case of this project analysis types 200 and 500 were not done (Figure 1) as it is not applicable.

2.2 Ventilation performance indicators

Air Changes per Hour (ACH) – (The preliminary approach)

The most widely used performance indicator for a ventilation system is air change per hour (ACH). ACH is the number of times per hour that a volume of air equal to the enclosed space volume is exhausted. For a positive pressure mechanically ventilated space ACH is calculated using equation 1.

$$ACH = \frac{3600q}{V} \qquad (1)$$

q is the fresh supply air flow (m^3/s)

V is the volume of the space (m^3)

WHO (2009) and CDC (2003) recommend 12 (ACH) in mechanically ventilated one bed TB isolation wards. Recently emerging guidance for healthcare buildings such as the Building engineering services guideline authored by the CSIR in collaboration with the National Department of Health has moved from expressing ventilation requirements from air-changes per hour (ACH) to volume flow rates per capita (L/ s/ person). The minimum requirement is 80 L/s/person for high risk areas such as waiting areas and TB treatment rooms.

The ventilation requirements for naturally ventilated spaces according to the WHO 2009, p.21 guidelines are as follows:

- Minimum of 80 L/s/per person for airborne precaution rooms,
- 60 L/s/per person for general wards and outpatient departments and
- 2,5 L/s/ m^3 for corridors and other transient spaces without a fixed number of patients.

The ventilation rates as calculated in Tables 3-5 were compared against the recommended ventilation rates specified in the WHO (2009) guideline.

Mean age of air

(Gao and Lee, 2011) used mean age of air as the ventilation performance indicator in their studies on evaluating the influence of openings configuration on natural ventilation performance of residential units in Hong Kong. Age of-air is a technique for evaluating ventilation that has been actively used for over 20 years. Age-of-air quantifies the time it takes for an elemental volume of outdoor air to reach a particular location or zone within the indoor environment. Age-of-air is often also used to quantify the ventilation effectiveness with respect to indoor air quality (Sherman, 1997). The mean age of air in a point is defined as the mean time that the air particles contained in a differential volume around the point have stayed inside the room. The youngest air will be found at outdoor air inlets, while the oldest air can be found at any other point, not necessarily at the outlets. For instance, if there is a stagnation region or a recirculation one, the mean age of air will be high in these areas and the ventilation will be poor (Mendez, et al., 2008). Mean age of air represents the average time that air spends in the same place till extraction. Mean age of air was also considered, especially in the design iteration phase; the aim was to obtain a design that exhibited the lowest mean age of air.

Ventilation rate measurement- tracer gas tests

Tracer gas techniques for measuring ventilation rely on the possibility of differentiating air already within the test room from new air coming into the space. The user should be able to either mark the air already in the space and follow how the marked air is replaced by new ventilation air; or mark the incoming air and measure how this marked ventilation air is distributed through the space. REHVA (2004) describes different tracer gas techniques for evaluating ventilation effectiveness:

- Tracer step down (concentration decay)
- Tracer step up method
- Pulse method
- Homogeneous constant emission method.

In this study the concentration decay method was used. CO_2 was used as the tracer gas. ASHRAE (1997) states that the calculations for ventilation rate using results of tracer gas concentration decay are based on a mass balance of the tracer gas within the space.

2.3 The Post Occupancy evaluation

According to (but not limited to) Meir *et al*. (2009) in their paper the authors define POE as: both qualitative and quantitative approach, but more importantly the value of design analysis post construction and in use, “Post-occupancy evaluation (POE) is a platform for the systematic study of buildings once occupied, so that lessons may be learned that will improve their current conditions and guide the design of future buildings. Various aspects of the occupied buildings’ functioning and performance can be assessed in a POE, both chemo-physical (indoor environment quality (IEQ), indoor air quality (IAQ) and thermal performance) as well as more subjective and interactional (space use, user satisfaction, and other).” It is from this very same perspective that a POE was undertaken to not only review the success of the intervention, but measure the success and acceptance by the user. The POE becomes a critical design feedback tool not only for analysis, or assessment but for critical design review. The POE in this research process incorporated the experimental test, observational assessment, and user qualitative response. The holistic POE outcome is not described in detail in this paper as more attention is given to the development of a design methodology as a tool for naturally ventilated building design.

3. Research Methodology

3.1 The CFD process and methodology

Using CFD software, a virtual model of four[2] of the Global Fund facilities were created, in order to simulate, visualize and analyse the ventilation performance of the initial design proposals. Subsequently the Brooklyn Chest Hospital in Cape Town was also simulated. The simulations developed from purely qualitative to quantitative as the process was refined. The simulation results led to revisions to the design proposals and directly informed the design development.

The ventilation efficiency of naturally ventilated buildings is complicated dependent on (Parsons *et al*., 2010):

- Climate zone – wind direction, speed and availability, temperature, humidity;
- Wind direction and profile;
- Site topography and latitude;
- Building geometry and roof angles;
- Interior obstructions and flow paths;
- Inner and outer temperature (buoyancy);
- Indoor air temperature which relates to incident solar radiation and thermal performance of building materials;
- Type and degree of envelope and building permeability;
- Adjacent structures and building location;
- Terrain; and
- Complimentary ventilation systems.

One of the most critical aspects for building performance testing is the creation of appropriate simulation models (Parsons *et al*., 2010). In the various case studies drawings were provided in different electronic formats. The most sophisticated drawings were created by the *Autodesk Revit 2009* Building Information System (BIM). In all cases the working drawings contained far too much geometric information for the simulation purposes. Building performance simulation models created for *Ecotect* or *Airpak* normally consist of simple and symbolic geometry that are supported by a significant amount of alphanumeric technical information. The emphasis is, therefore, more on the technical alphanumeric attributes than the detailed geometric representation. For example a simple multi-layered wall is represented by a simple geometric surface in simulation software and a set of technical/ engineering alphanumeric values that handle inter alia values such as U-value (W/m².K) and Admittance (W/m².K). At the time of the project the interoperability between CFD and CAD was a key barrier to the general technology uptake of CFD in the built environment.

Figure 2 illustrates the measures that were taken to maximise the air flow through the spaces. These were qualitatively simulated by CFD. The roof angle was specifically made 25° so that when air moves across the roof the windward side would develop a positive pressure and the leeward side negative pressure. This directly improves the ventilation efficiency of the roof ridge ventilation. A literature study (ASHRAE, 2005) and CFD simulations indicated that this pressure difference phenomenon would be fully developed at a roof angle of approximately 25°. Due to the unpredictability of the wind direction and in an attempt to make the ridge ventilation more effective various literature studies, CFD simulations, field studies and laboratory tests were undertaken. Conventional wisdom at this stage was that wind driven roof ridge turbines, also known as

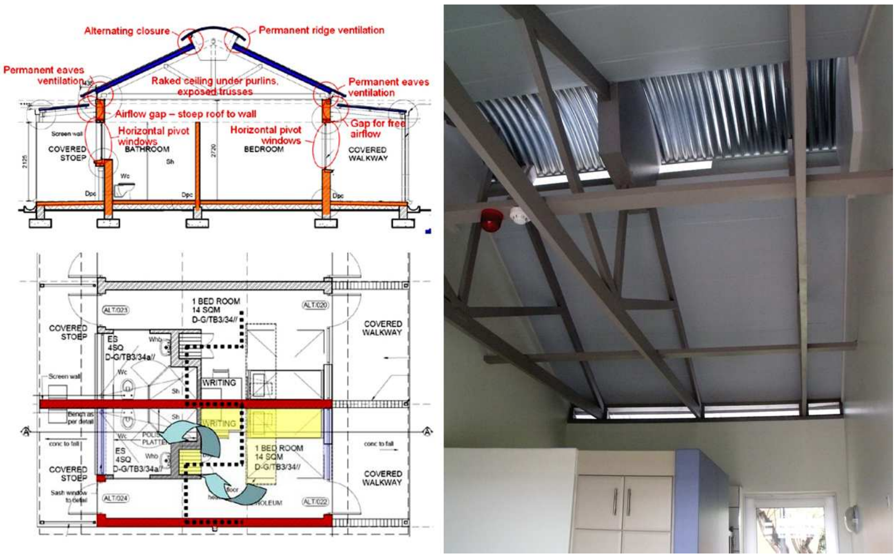

Figure 2 The natural ventilation design of the wards for maximising natural ventilation (authors).

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[2] Jose Pearson, Manguzi, Catherine Booth and Modimole

"whirlybirds" would be adequate. The findings of field tests and a laboratory study (Salie, 2014) clearly indicated clearly that the installation of the turbine ventilator did not increase the ventilation flow rate in all natural ventilation configurations. Further CFD simulations were undertaken and it was discovered that permanent ridge ventilation with alternating closures would be the best solution (Figure 2). This solution combined with a roof angle of 25° proved to be omni directional and effective.

Other interventions are a very large openable window area (25% of floor area) in a cross ventilated configuration. To ensure an omni-directional and effective flow of air horizontal pivot and hopper openable windows were extensively used in the various projects. This was enhanced by permanent eaves ventilation slots and a gap for free airflow in the roofs of the covered walkways. The total volume of the space is 61.4 m^3. This is a very large volume for a single patient.

3.2 The Carbon Dioxide (CO_2) decay methodology

The tests and experimental measurements were done in the following stages:

1) The CO_2 concentration was first measured in the room and the outside ambient air. This was done to determine the background CO_2 concentration in the room air and to check for unknown sources of carbon dioxide nearby.

2) CO_2 gas was injected into the ward from the CO_2 cylinder. Mixing fans were used to disperse and mix the injected carbon dioxide gas. The concentration of CO_2 in different parts of the ward was monitored at two points at 1.1m height above finished floor level that would be the breathing zone for sleeping patient by a SENTRY ST-303 non-dispersive infrared CO_2 gas sensor. This was done to confirm uniformity of concentration of the tracer gas in the ward as stipulated by REHVA (2004) and ASHRAE (1997). Demmers, et al. (2001) suggests that the best sampling points of the tracer gas is at the outlets, if inlets and outlets are well defined. However, in naturally ventilated buildings an air opening can be an inlet or outlet depending on the prevailing wind direction. Therefore the average tracer gas concentration taken at the two points in the ward was assumed to be the exhaust concentration.

3) When a uniform and sufficiently large concentration (less than 5 000 ppm) of carbon dioxide gas was achieved, the fans and carbon dioxide injection were stopped. The openings associated with the respective test scenarios (See Table 2 key for different test scenarios) were opened, and the tracer gas was allowed to decay naturally.

3.2 The Post Occupancy Evaluation (POE) methodology

A Post Occupation Evaluation assessment was developed to gage the expected projected outcome versus the factual final site outcome. The CSIR developed a prototypical design layout as guidelines to facilitate architects and the consultant team with the added benefit to communicate the architectural philosophy and spatial layout for airborne diseases design to hospital staff. Computer aided air movement modelling (computational fluid dynamics) was used during the development of both passive and natural ventilation systems to ascertain an effective cross ventilation design.

The methodology of assessment required both testing and interviews

1) Firstly: a formal meeting was held with all relevant staff members within the new facility, provincial department representatives and members of the consulting team. Individual interviews were conducted with staff members; and a debriefing interview was done with the architect/principle agent.
2) Secondly, but simultaneously: a scientific test was done in one of the new patient bedrooms, using tracer gas methodology by means of CO2 release to saturation (±5000 ppm) and measuring the decay rate in assessing the number of air changes achieved within the hour. Comparing these rates to world standards and thus the effectiveness of the design specifically with regards to air change rates as described in detail in section 3.1

4. Findings and Discussion

4.1 Findings from the CFD modelling

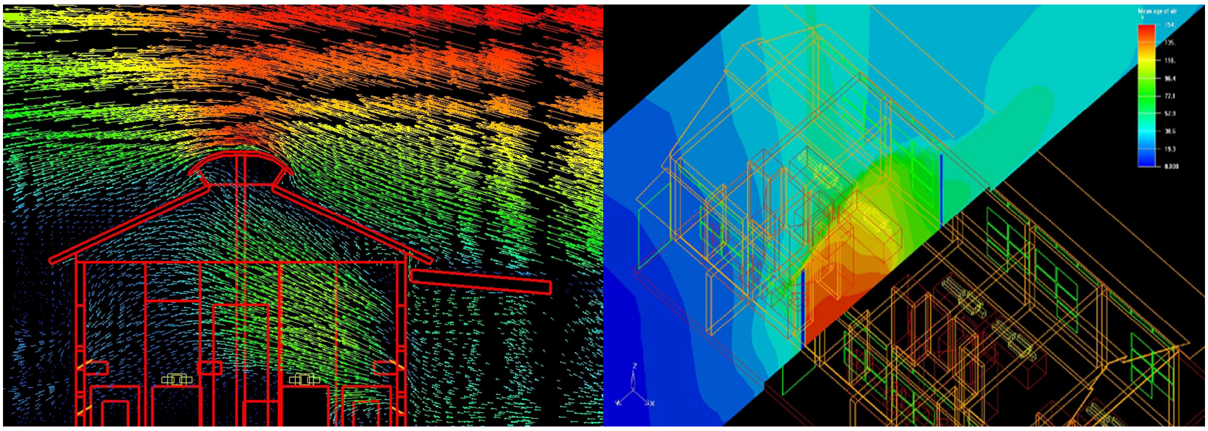

Figure 3 *Qualitative and quantitative CFD studies undertaken for the Modimole [roject. The left illustrates the development of an efficient roof ventilator and right the ventilation effectiveness in terms of MAA.*

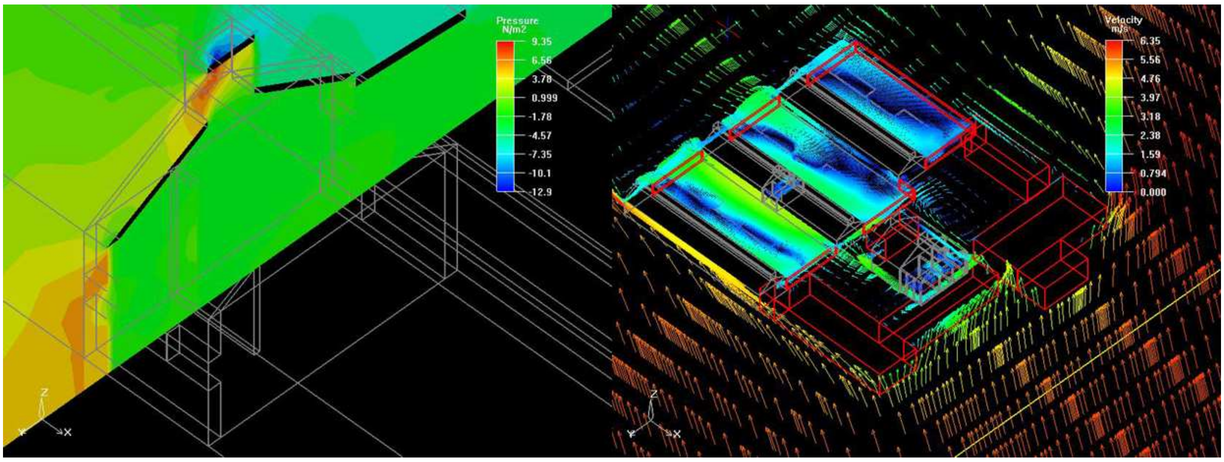

Figure 4 *Pressure development over the Brooklyn Chest roof on the left and external wind studies to determine the boundary conditions for the detailed interior models on the right.*

Figure 3 (left) illustrates the CFD simulations that were used in the Modimole project to improve the effectiveness of the permanent roof ventilation. Various roof ventilation designs were explored to ensure proper mixing of the fresh outside air with the interior contaminated air. It was also used to test the ventilation effectivity of the windows. In the particular example an outside air speed of 4 m/s was used. Figure 3 (right) illustrates an analysis of Mean Age of Air (MAA). In the particular example the MAA varies from 77 s on the windward side to 154 s in the far side of the room (leeward side).

Figure 4 illustrates CFD simulations that were undertaken at the Brooklyn Chest project. Figure 4 (left) illustrates the effect of air movement over the building with a roof angle of 25°. On the windward side a positive pressure of 3.78 and 9.35 N/m² develops and on the leeward side negative pressures between -12.9 and -1.78 N/m², relative to atmospheric pressure. The alternating closure method that was developed for the Modimole project (Figure 1) was used in the Brooklyn Chest rectangular roof ventilator. Figure 4 (right) illustrate one of many external wind studies that were used to determine the boundary conditions for the detailed interior CDF models under various wind directions, strengths and heights. In this case it was a wind of 6 m/s from a south-easterly direction.

Table 1 *ACH analysis for Brooklyn Chest*

Air Change per Hour Analysis for Brooklyn Chest			
Block Name	**Wind Direction**	**ACH with wind speed 1 (6 m/s)**	**ACH with wind speed 2 (1.5 m/s)**
South Block	South-east	58.368	19.293
Middle block	South-east	50.685	8.278
	West	54.185	17.347
	North-wind	63.500	18.560
Consultation Room	South-east	[3]192.931	
	West	[4]142.723	

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[3] This number is very high because it was assumed that the door is open. If the door is closed then open able windows will have to be provided at lower level.

[4] As in 2 above the number is very high because the door was assumed open.

4.2 Findings from the Carbon Dioxide (CO_2) experiment

The decay in concentration of the carbon dioxide was plotted as illustrated in the graph of Figure 5. The exponent of the equation of the graph of Figure 5 was multiplied by 60 to obtain ventilation rate in ACH. All the results for the test scenarios are shown in Tables 3-5.The value of ventilation rate in L/s in the last row of Tables 3-5 was calculated using the formulae in equation 3.

$$Ventilation\ rate\ \ (l/s) = \frac{ACH \times roomvolume\ \ (m^3)}{3600 \times 0.001} \qquad (3)$$

Table 2 Key for ventilation scenarios

Key	**Definition**
AWDC	All Windows and Door Closed
RMO	Roof Monitor Operational
SGO	Side Grills Operational
AWDO	All Windows and Door Open
3GO	3 Grills Operational
AWOEDO	All Windows Open External Door Open
THDO	Top Half Door Open
MWBSO	Middle Windows Bathroom Side Open
BWWSO	Bottom Windows Ward Side Open
4TWWSO	4 Top Windows Ward Side Open
3TWBSO	3 Top Windows Bathroom Side Open
HTDO	Half Top Door Open
ABSWC	All Bathroom Side Windows Closed
WSWDO	Ward Side Windows and Door Open

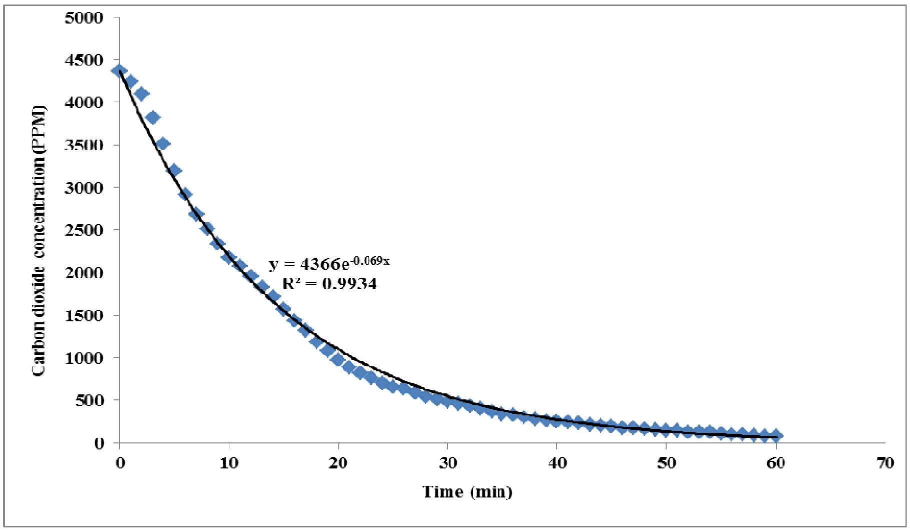

Figure 5 Tracer gas concentration decay for mostly closed ventilation openings at Modimolle hospital See Table 3.

Table 3 Quantified ventilation performance for mostly closed ventilation openings

Hospital	**Jose-Pearson**	**Catherine Booth**	**Modimolle**
Climatic region	Bsh (E.C)	Csa (KZN)	Bsh (Limpopo)
Wind speed (m/s)	8.4	5	0.8
Wind direction	SW	N	NW
Ward type	1 bed En-suite	2 bed En-suite	1 bed En-suite
Ventilation system	Natural	Natural	Natural
Openable area	6.95	11.9	9.35
Floor area	13.8	24.94	17.82
Ventilation scenarios investigated	AWDC,RMO	AWDC, SGO, RMO	AWDC, SGO, RMO
Ward volume (m^3)	59	68	61
Measured ventilation rate (ACH)	**17.4**	**14.2**	**4.1**
Ventilation rate (l/s/patient)	**285**	**133.7**	**69**

Table 4 Quantified ventilation performance for mostly opened ventilation openings

Hospital	**Jose-Pearson**	**Catherine Booth**	**Modimolle**
Climatic region	Bsh (E.C)	Csa (KZN)	Bsh (Limpopo)
Wind speed (m/s)	8.4	2	0.9
Wind direction	SW	N	NW
Ward type	1 bed En-suite	2 bed En-suite	1 bed En-suite
Ventilation system	Natural	Natural	Natural
Openable area	6.95	11.9	9.35
Floor area	13.8	24.94	17.82
Ventilation scenarios investigated	AWDO,RMO	AWDO, SGO, RMO	AWDO, SGO, RMO
Ward volume (m^3)	59	68	61
Measured ventilation rate (Ac/h)	**38.9**	**25.1**	**20.5**
Ventilation rate (l/s/patient)	**638**	**237.1**	**347**

Table 5 Quantified ventilation performance for typical ventilation opening scenarios.

Hospital	**Jose-Pearson**	**Catherine Booth**	**Modimolle**
Climatic region	Bsh (E.C)	Csa (KZN)	Bsh (Limpopo)
Wind speed (m/s)	8.4	*2*	*0.9*
Wind direction	SW	*N*	*NW*
Ward type	1 bed En-suite	*2 bed* En-suite	*1 bed* En-suite
Ventilation system	Natural	Natural	Natural
Openable area	6.95	11.9	9.35
Floor area	13.8	24.94	17.82
Ventilation scenarios investigated	THDO,RMO,MWBSO, BWWSO	*AWDO, SGO, RMO*	*AWDO, SGO, RMO*
Ward volume (m^3)	59	*68*	*61*
Measured ventilation rate (Ac/h)	**21.3**	***25.1***	***20.5***
Ventilation rate (l/s/patient)	**349**	**237.1**	**347**

4.3 Findings from the Post Occupancy Evaluation (POE)

The research process developed by the CSIR through various design criteria, modelling and user experience studies have produced improved the air quality of the facilities, created safer patient and nursing spaces and set a minimum standard for future designs. Thermal comfort was a noted concern with numerous comments on the driving rain through the roof top ventilations and the cold conditions in the ward rooms. These challenges can be overcome without compromising the project and airflow design. Potential solutions included utilising weather louvres at the roof ridge and installing infrared heaters in the ward rooms with additional supply of blankets to patients.

The project allowed for the development of a baseline design standard to be built upon and improved for future facilities.

5. Conclusion and Further Research

When considering the various scenarios studied the following observations have been made: For the case where ventilation openings are mostly closed, for example, the ventilation rate for Modimolle did not comply with the WHO (2009) guidelines (Table 3). Therefore the ward natural ventilation systems for Modimolle hospital must never be operated as outlined in row 9 of Table 3. This is largely due to the low ambient wind conditions and climatic region. For the case where ventilation openings are mostly closed, the ventilation rate for both Jose Pearson and Catherine Booth hospitals complied with the WHO (2009) guidelines (Table 3). Therefore for the external wind speeds recorded (see row 4 Table 3), the natural ventilation systems for these hospitals can be operated as outlined in row 9 of Table 3.

Lastly, for the case where ventilation openings are mostly opened, the ventilation rate for all the hospitals complied with the WHO (2009) guidelines (Table 4).

The ventilation rate is proportional to the external wind speed where windows where mostly open. Therefore it can be concluded that the higher the opening area (openings which separate the air in the ward interior to outdoor air), the higher the ventilation rate (number of ACH). This conclusion is evidenced by larger ventilation rates for scenarios where ventilation openings were mostly opened when compared to the scenarios where ventilation openings are mostly closed. Therefore it is highly recommended for optimum ventilation performance of the wards that all openings to the exterior environment to be permanently opened.

The results of the study indicate that the CFD methodology and various iterations of design solutions did add value and contributed to the improved ventilation rates found in the various facilities. The roof ridge design and top-light air ventilators are a direct outcome of iterative CFD analysis. This played a governing role in the improved airflow and rates in especially 'closed' environments, where it otherwise would have been little to no ventilation. Utilizing CFD simulation is a viable option for both testing design options towards predicting natural ventilation flow patterns for built environment design.

The POE indicated that the implementation of a built environment design by research solution for high risk areas of TB infection. The research created indicators and valuable data in a series of design initiatives employed within a variety of climatic regions and wide spectrum of patient demographics. It is evident though the various staff interviews and project team discussions that the new facilities have improved nursing and patient ward standards.

6. Acknowledgement

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