

Researched solutions for long-term accommodation units for drug-resistant tuberculosis patients in South Africa

Sidney Parsons¹, Geoff Abbott¹, Peta de Jager¹, Dirk Conradie¹, Sheldon Bole¹

¹CSIR Built Environment, PO Box 395, Pretoria, 0001

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Abstract

South Africa has been ranked as one of the 22 high-burden TB countries in the world by the WHO, and is also burdened with a high prevalence of HIV/AIDS. TB, both in its drug-susceptible and drug-resistant form, is the most common opportunistic infection for HIV patients and actively accelerates the progression of HIV into AIDS. Active treatment and reduction of opportunities for cross-infection are therefore high priorities in South Africa. TB is transmitted through the airborne route: poorly designed or overcrowded buildings and other closed congregate areas such as public transport form important transmission nodes.

The CSIR was approached by the National Department of Health (NDoH) to research and facilitate the design and construction of new long-term accommodation units for some 400 patients in 9 centres across the country in a project funded by The Global Fund. The project required the Architectural Sciences group of CSIR Built Environment to act both as technical advisor to NDoH and provincial recipients for the planning, design and construction of the units as well as to manage project implementation. The project has provided a unique opportunity to review current policy, to develop guidelines for long-term accommodation of patients with drug-resistant TB and to research, test and validate the performance of accommodation units provided through the project. The project has also provided valuable insight into facility risk assessment and design guidelines for other types of public buildings.

The planning and design of such facilities must recognise not only health care needs, but also the social and personal needs and safety of patients and staff. Full use was made, wherever possible, of natural ventilation and environmentally sustainable design solutions. The design solutions are being tested for efficacy using CSIR's newly developed Building Performance Laboratory primarily through the use of computational fluid dynamics (CFD) modelling. Once completed and occupied, projects will be tested and validated against predicted and desired performance standards. The first unit was occupied in October 2009; it is expected that the last will be occupied early in 2011.

1. Introduction

1.1. Drug-resistant TB in South Africa

Of the estimated 8.9 million new cases of tuberculosis (TB) in the world in 2008, 476 000 or just over 5% occurred in South Africa. As one of the designated 22 high-TB burden countries, which together account for 80% of all cases globally, South Africa had the highest incidence rate of 960 new cases per 100 000, far above the average rate of 178 for high-burden countries and the global incidence rate of 138 per 100 000 (figure 1). Africa carries a particularly high burden: the WHO Africa Region has twice the rate of the South East Asia Region, which is the next most infected region (351 / 184 cases per 100 000).

Approximately 90% of new TB cases are drug susceptible and can usually be successfully treated with first-line drugs. The remainder are drug resistant, either multi- (MDR) – where the patient is resistant to first-line drugs, or extensively drug resistant (XDR) where there is also resistance to the second-line drugs

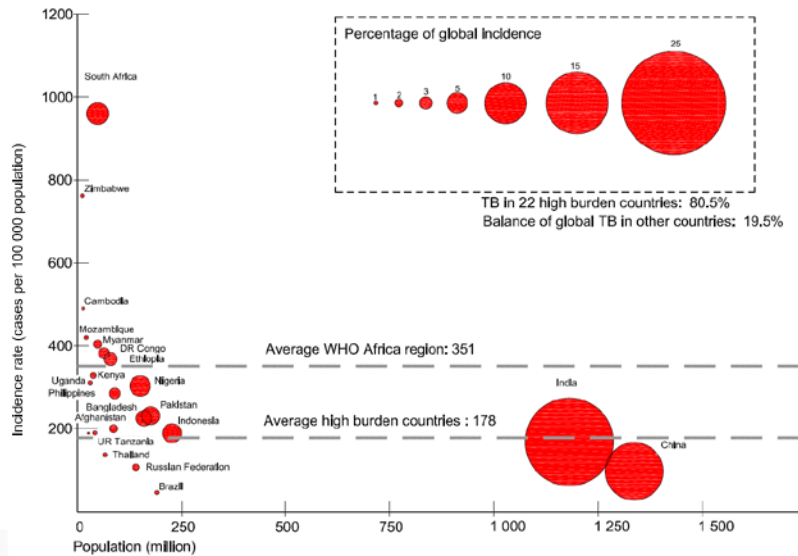


Figure 1 : Global incidence for all TB in 2008 showing percentage of global incidence and incidence rate per 100 000 population

MDR-TB is currently less than 40% (NDoH, 2010) and substantially lower for XDR-TB. However, despite the greater treatment cost, WHO stresses that diagnosis and treatment of DR-TB is feasible and an important component of the STOP-TB strategy by reducing ongoing transmission, future burden and service cost (WHO, 2008).

The WHO has identified 27 countries that together account for 85% of DR-TB globally. South Africa had the fourth-highest number of MDR cases in 2007 and, at 32 per 100 000, the highest incidence rate of the high-burden countries (WHO, 2009). This high burden in South and southern Africa is driven to a significant extent by the HIV/AIDS pandemic. TB is the most common opportunistic infection for those living with HIV/AIDS, with the growth in the number of cases of TB closely tracking the spread of HIV/AIDS. (NDoH 2007). It is estimated that 71% of all TB cases in South Africa are also HIV/AIDS positive (WHO, 2009).

1.2. TB transmission and the built environment

TB is an opportunistic airborne infection which can affect anyone. However, the risk of infection is higher among those who are immunocompromised – HIV/AIDS is a high risk factor but other factors include diseases such as diabetes, indoor air pollution (often associated with indoor use of solid fossil fuels), malnutrition, tobacco use and alcoholism (WHO, 2010). Transmission usually occurs in poorly ventilated congregate settings, such as in overcrowded housing conditions, in transport (taxis, buses and trains), or in communal spaces in poorly designed and managed public buildings where high-risk factors are present.

Transmission is initiated when the TB bacterium, *Mycobacterium tuberculosis*, from an infected lung site of an infected person becomes aerosolised in small droplets (usually liberated in substantial quantities through coughing, sneezing or singing). A large proportion of smaller droplets ($\approx \text{Ø}10\mu$) evaporate, crystallising into bacteria-bearing “droplet nuclei”. These remain airborne following room air currents. Infection can occur when the bacterium carried by the droplet nuclei is inhaled and lodges in the alveoli of the lungs. The infection site may remain dormant or, depending on local conditions and risk factors, may spread, usually within the lung but may spread to other areas in the body. Studies at the AIR laboratory¹ at Witbank TB hospital have demonstrated very high levels of infectivity of air drawn from a ward occupied by DR-TB patients.

¹ The AIR Laboratory is a joint initiative of the CDC, Johns Hopkins and Harvard Universities, the MRC and the CSIR.

used for MDR-TB patients. The drug regime used for MDR and XDR-TB is more toxic and significantly more expensive than those required for drug-susceptible TB. Treatment takes longer, is less effective and has more serious side effects. Patients remain infectious on treatment until they convert to smear negative, usually a period of 6 months or more.

Drug-resistant TB (DR-TB) generally develops as a result of treatment failure where first-line drugs are not controlled or where treatment is not completed, but may also result from primary infection (WHO, 2008). Treatment success for

There are many strains of TB and drug-resistant TB, and a person may be infected or re-infected by more than one strain. The risk of infection is increased where the concentration of droplet nuclei is high – usually areas with high generation (such as multi-bed DR-TB wards or waiting areas) and inadequate ventilation, and with increased duration of exposure (Parsons et al, 2008).

Certain areas in health care facilities, such as out-patient waiting areas, consulting rooms, X-Ray departments and medical or TB inpatient wards and laboratories, are high-risk areas. Studies of the outbreak of XDR-TB at Church of Scotland Hospital (CoSH) in 2005-06 indicated that most of the cases, which resulted in both patient and staff deaths, were probably as a result of nosocomial infection in the hospital (Ghandi et al, 2006). A hazard analysis undertaken by the CSIR at CoSH identified several critical control areas where the risk to patients and staff was particularly high (Parsons et al, 2008). Figure 2 shows a generic process flow diagram identifying HACCP points developed from the CoSH study.

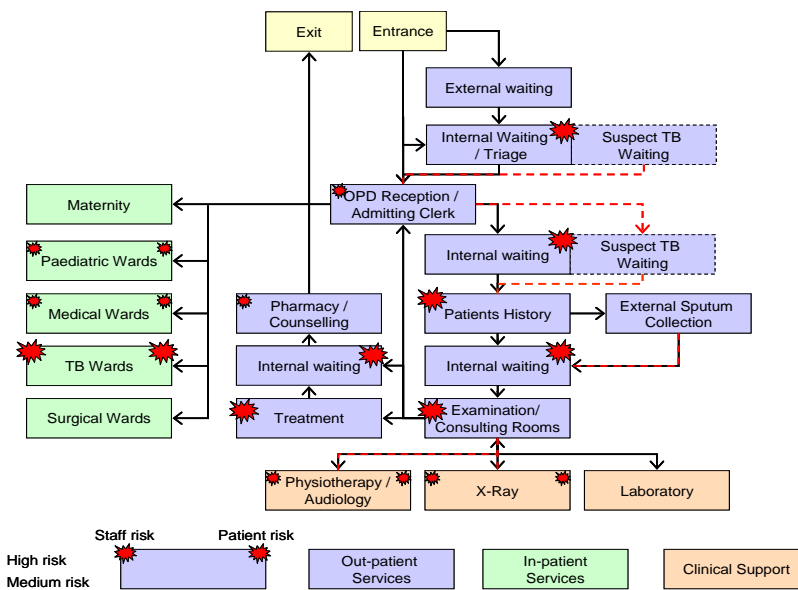


Figure 2: District hospital flow and HACCP point analysis diagram

Hospital staff – including those in direct service contact and support staff (including cleaning and maintenance staff) – are generally at high risk, particularly in out-patient areas where cases still need to be detected and the risk is perceived as lower than in TB wards and where inadequate infection control practices are in place.

Other building types where the risk is high include prisons and detention centres, schools and churches in poor and vulnerable communities, social service access points and other congregate settings including taverns, banks, post offices, waiting areas in other government offices, refugee

centres and camps for displaced persons. It is also recognised that congested public transport and transport nodes and the transport of patients from one facility to another create high-risk opportunity areas that need to be managed (NDoH, 2010).

1.3. Evolving TB policy in South Africa – from inpatient to decentralised care model

Unlike drug-susceptible TB which becomes non-infectious shortly after treatment initiation, drug-resistant TB remains highly infectious under treatment. The current accepted indicator that a patient is no longer infectious is when the patient sputum culture results have converted from positive to negative. This can take a treatment period of 6 months or longer. Treatment policy in South Africa has required the hospitalisation of all patients with drug-resistant TB until such time as they have two consecutive negative TB cultures at least a month apart (NDoH, 2007).

Increasing infection rates, improved case finding and improved laboratory and diagnostic procedures have led to increasing numbers of patients requiring hospitalisation and long waiting lists for available beds. In 2009 there were 5 427 registered MDR- and XDR-TB patients against 1 854 available beds (NDoH, 2010). Meeting the accommodation needs both in terms of satisfying the required bed numbers and in providing a safe and humane environment provides a significant challenge. Accommodation has been provided for patients in existing TB hospitals converted for DR-TB use or in new units attached to existing district or

regional hospitals. The reuse of existing TB hospitals is problematic as most were designed with large open wards which, while suitable for drug-susceptible TB, are not appropriate for highly infectious DR-TB.

Recognising the unmet need for additional capacity and the high risk of the spread of the disease from increasing numbers of patients held in communities waiting for treatment², NDoH introduced a new decentralisation treatment policy in 2010 (NDoH, 2010). The policy provides for five levels of care with admissions either into the central provincial centre of excellence (both MDR- and XDR-TB cases) or into a decentralised unit (for MDR-TB) with patients referred down as their condition stabilises through a referral network into satellite MDR-TB units closer to their home communities, and out into home-based services provided by PHC-based injection teams and community DOTS supporters. All home-based patients are managed and monitored through out-patient services run from all levels of service (figure 3).

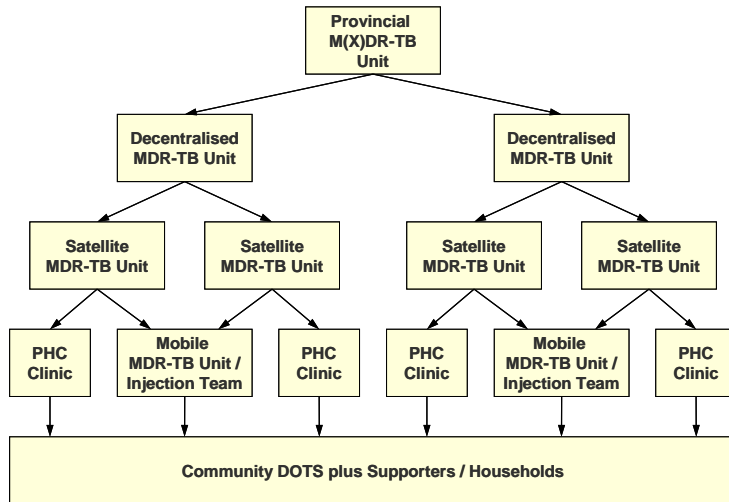


Figure 3: Framework for decentralised management of TB

designed for the management of infectious diseases, particularly not for DR-TB. Existing wards in district and referral hospitals will need to be converted and used for DR-TB services and DR-TB patients will need to acquire other support services in these hospitals including radiography, physio- and occupational therapy and, on occasion, surgery.

While infrastructure discussion under the previous hospitalisation policy focused on the design of new purpose-designed long-term DR-TB facilities, greater emphasis is now being placed on infection control at all facilities. While new facilities will still be built under the new decentralisation policy, there will be an increased focus on the remodelling and conversion of existing facilities to accommodate decentralised and satellite services for DR-TB. There is also a specific need to address all healthcare facilities where case finding takes place.

A further infrastructure design and administrative implication is around the roll-out of antiretroviral therapy (ARV) to HIV-positive patients. With the high level of co-infection, many TB patients are HIV positive and will be put onto ARVs and require active and ongoing monitoring and management. However, TB is a highly infectious disease and uninfected HIV patients are immunocompromised and at high risk for nosocomial infection. Effective policy, procedures, use of infrastructure and alterations are required in order to reduce the risk of infection transmission.

² WHO estimates that person with open tuberculosis would infect 10-15 people per year (WHO, 2009)

With the new policy, patients are now brought into the treatment regime and stabilised at an earlier stage, with shorter hospital stays and earlier release of patients into a controlled out-patient treatment environment. While patients may not have fully converted by the time they are released into a home-based care programme, they are less infectious and, with appropriate awareness and skills training are better positioned to manage their status and interaction with the community in a responsible manner.

The infrastructure implications are that DR-TB services will now be provided from more centres, most of which will not have been originally

1.4. Managing TB and airborne disease transmission in health care settings

The World Health Organisation, in its handbook for implementing the Stop TB strategy (WHO, 2008), highlights the internationally accepted hierarchy of control measures:

- administrative control measures to improve management procedures and reduce opportunities for cross infection
- environmental controls to reduce the concentration of infectious droplet nuclei, and
- personal respiratory protection in specified areas where administrative and environmental controls do not provide adequate protection.

Administrative measures offer the first line of defence and include setting up infection control policy, training of staff and patients, identification and management of risk situations such as triaging to separate out patients with TB symptoms from out-patient queues, and reduction of overcrowding in wards. Administrative measures can be translated into physical design such as through creating separate or outdoor waiting areas or the physical separation of staff duty areas from inpatient areas. Recognition of HACCP points and design to reduce risk is essential.

Environmental controls are supplementary to administrative controls and are intended to reduce the risk of transmission through reducing the concentration of infectious droplet nuclei in areas where patients are present. This may be achieved through natural or mechanical means. Ideally, in resource-constrained settings the focus should be on natural means as these normally offer a cheaper capital and operating cost solution requiring less ongoing maintenance. Reliance on natural ventilation requires administrative support in ensuring that windows and doors are kept open or that sufficient permanent ventilation is provided to ensure the required number of air-changes. This can be problematic in areas where there are severe winters.

In some cases it is necessary to revert to mechanical ventilation systems – in these cases the system needs to be designed appropriately to ensure adequate pressure cascading and flow of air away from 'safe' areas (staff offices, nursing station) to TB patient areas. The use of paddle fans to mix air in patient rooms to counter clumping of droplet nuclei (creating highly infectious pockets) may be indicated.

The use of ultraviolet germicidal irradiation (UVGI) units is appropriate in certain situations. These units are used as upper-room irradiation units and have been shown to be effective in killing TB bacilli especially under low-humidity conditions (Dharmadhikari et al, 2010). Appropriate specification and design are essential. They require ongoing maintenance and, if not properly monitored and maintained, can provide a false sense of security.

The final protection level is the use of respirators as personal protection devices where staff need to work in high-risk areas. These respirators are made up of high-efficiency particulate filtration material designed to filter out droplet nuclei ($> \varnothing 0.3\mu$). Ordinary surgical masks used by patients can be highly effective in capturing a large proportion of droplets at source before they have the opportunity to nucleate.

2. Drug-resistant TB infrastructure projects

Recognising the substantial shortfall in the number of beds available for the long-term care of drug resistant TB patients, an approach was made by NDoH to The Global Fund (GF) in 2008 for targeted capital funding for an additional 342 beds at eight designated sites in seven provinces. An amount of US\$12,3m was made available by the GF late in 2008 and CSIR was approached by NDoH to act as implementing agent for the project, a role which included technical input and support to all project teams, as well as overall project and financial management and the channelling of project funds to recipient provinces. The GF required that all projects be completed by the end of December 2010.

It was recognised that some provinces would want to add additional capacity and functionality to their sites over and above that identified in the initial application to the GF. The strategic service plan for Modimolle hospital in Limpopo, for instance, required a unit that would develop in time to 200 beds from the current 50 beds. The first phase of the GF project moved from an initial planned upgrading of a 12-bed unit in the

existing 50-bed hospital, to a fully supported upgrade and extension to 100 beds, all planned and designed as part of the initial GF project but with supplementary provincial funding (table 1).

The project target sites are located in seven of the nine provinces and are located in a range of different locations and climatic zones across South Africa. Projects also ranged from upgrading of existing buildings where there was a basic constraint provided by the existing building shell, to new units in which there was planning and design freedom to introduce new infection control measures.

Table 1: Overview of Global Fund projects

<i>Province</i>	<i>Location</i>	<i>Hospital</i>	<i>Description</i>	<i>Beds</i>	<i>Final beds</i>	<i>GF budget</i>	<i>Total project</i>
Eastern Cape	Port Elizabeth	Jose Pearson TB	New unit on existing site	40	40	13 329 112	14 355 137
Free State	Welkom	Kopano	Convert existing maternity centre	60	60	10 867 421	29 675 027
KwaZulu-Natal	Manguzi	Manguzi	New unit on existing site	40	40	9 276 250	9 276 250
KwaZulu-Natal	Amatikulu	Catherine Booth	New unit on existing site	40	40	11 947 810	14 778 891
Limpopo	Modimolle	Modimolle	Upgrade, expand existing hospital	12	100	5 097 474	57 428 083
Mpumalanga	Hazyview	Bongane TB	Upgrade, expand existing hospital	40	40	13 329 112	18 640 967
Northern Cape	Kimberley	West End	Convert existing psychiatric hospital	40	40	13 329 112	19 888 388
North West	Klerksdorp	Tshepong	New unit on existing site	40	40	13 329 112	41 507 307
Totals				324	400	90 505 403	205 550 050

In January 2010 NDoH reallocated R2m GF funding to convert two wards for drug-resistant TB in the existing Nkqubela TB hospital in Mdantsane, adding a second project in the Eastern Cape. In June 2010 the CSIR was appointed by the Western Cape Department of Health to provide technical support to a new project for 60 new XDR-TB beds at Brooklyn Chest Hospital, the designated provincial TB centre of excellence. This project adds a winter-rain climatic zone demanding an alternative design approach.

Each project has been set up working through the provincial TB directorate and provincial capital planning structures using a local team of professional consultants for the development of the design, documentation and implementation of the projects. An introductory session was held with each team at the outset of the project where training was provided in DR-TB, in managing TB infection control through building design and in natural ventilation and sustainable design principles. Each team produced a phased master plan for the redevelopment of the site addressing the principles outlined below, which was subject to technical review. In some cases it was possible to build a comprehensive first phase using supplementary provincial funding, in others only basic accommodation could be provided from the available GF allocation.

3. Project development

3.1. Design principles

The need to provide an appropriate balance between the high demand for beds, appropriate care and the limitations of a resource-constrained developing country were also recognised. Key principles identified included patient and staff safety through appropriate infection control measures, the provision of an environment supporting an appropriate level of health service delivery, recognition of patients' dignity and needs, low life-cycle costs and sustainability. These principles were consolidated into the following broad design guidelines for master planning and the DR-TB infrastructure projects:

- Where possible patients to be accommodated in single rooms with en-suite ablutions
- Physical separation of a 'safe' staff zone (nursing station and support rooms) from patients 'infectious' zone
- Creation of a cluster close to the nursing station for patients requiring acute care with high visibility
- Visibility and control from the nursing station of all rooms and the unit as a whole
- The use of natural ventilation as far as possible in all patient areas to achieve maximum air changes at all times (target minimum of 12-16 air changes per hour)







- Provision for direct nursing and clinical support services including clean and dirty utility, storage, and pharmaceutical services
- Provision for patient support including outdoor areas for daytime use, recreation areas, spiritual needs, development (education for the youth and adult education and skills development), visitors facilities and grounds for sports and gardening
- Provision for clinical support available to the unit including consulting rooms, psychiatric and social support, occupational and physiotherapy
- Provision for administrative and domestic support services including administration, catering services, cleaning, laundry, bulk supplies and mortuary
- Provision for security including appropriate controlled access and security fencing.



All projects are being built at existing health facilities (without disrupting services) and it was a requirement that project teams develop an overall master plan showing the integration of the new unit into a long-term development strategy for the facility. Provision needed to be made for services required by new emerging service policy (both at national and provincial level) – such as out-patient services at all facilities - as well as for a review and rebalancing of hospital support services.

3.2. Design development

The broad principles were supported by an initial concept design developed by the CSIR to provide an example of how the principles could be converted into a design for new projects. The principles were adapted differently by each team in response to contextual clues such as the existing infrastructure, climate conditions and construction technology. Table 2 illustrates the concepts adopted for the different projects and outlines key variables.

Table 2: Key variables and layout typologies for the original eight Global Fund projects

<p><i>Location</i> •Port Elizabeth, Eastern Cape</p> <p><i>Hospital</i> •Jose Pearson</p> <p><i>Beds</i> •40 - 40x1</p> <p><i>Description</i> •New XDR accommodation unit in existing 340 bed facility</p> <p><i>Ventilation</i> •Natural</p>		<p>•Welkom, Free State</p> <p>•Kopano</p> <p>•45 - 17x1, 4x2, 5x4</p> <p>•Conversion of existing maternity hospital into full MDR-TB unit</p> <p>•Mechanical</p>	
<p><i>Location</i> •Manguzi, KwaZulu-Natal</p> <p><i>Hospital</i> •Manguzi</p> <p><i>Beds</i> •40 - 4x10</p> <p><i>Description</i> •New integrated MDR-TB unit linked to existing district hospital</p> <p><i>Ventilation</i> •Mixed mode</p>		<p>•Amatikulu, KwaZulu-Natal</p> <p>•Catherine Booth</p> <p>•40 - 12x1, 14x2</p> <p>•New MDR-TB integrated unit adjacent to existing district hospital</p> <p>•Natural</p>	
<p><i>Location</i> •Modimolle, Limpopo</p> <p><i>Hospital</i> •Modimolle</p> <p><i>Beds</i> •62 - 62x1</p> <p><i>Description</i> •Additions to and phased conversion of existing 50 bed DR-TB hospital</p> <p><i>Ventilation</i> •Natural</p>		<p>•White River, Mpumalanga</p> <p>•Bongane</p> <p>•40 - 14x1, 13x2</p> <p>•Additions to and phased conversion of existing xx bed TB hospital</p> <p>•Natural</p>	

Location	<ul style="list-style-type: none"> •Kimberley, Northern Cape •West End 		<ul style="list-style-type: none"> •Klerksdorp, North West 	
Hospital	<ul style="list-style-type: none"> •44 - 36x1, 4x2 		<ul style="list-style-type: none"> •Tshepong 	
Beds	<ul style="list-style-type: none"> •Conversion of existing psychiatric hospital into MDR-TB unit added to existing xx bed 		<ul style="list-style-type: none"> •40 - 16x1, 12x2 	
Description	<ul style="list-style-type: none"> •Natural 		<ul style="list-style-type: none"> •New MDR-TB unit and out-patients to existing 58 bed M(X)DR-TB unit at existing referral hospital 	
Ventilation			<ul style="list-style-type: none"> •Natural 	

Spatial layout of various rooms was optimised for reducing infection risk, whilst maintaining high nursing visibility using efficient staff to patient ratios. 'Acute' patient rooms were clustered close to nurses' station for newly admitted patients to allow for patients to be stabilised on their TB medication and for the control of other opportunistic infections. Other 'post acute' rooms to be grouped further away from the nurses' station but all rooms to be visible from the nurses' station allowing ongoing control of the unit. The nurses' station and nursing support rooms were to be physically separated from the patient rooms by an open corridor so that the nurses' station can be treated as a safe haven where nursing staff are fully protected from any chance of airborne infection.

Recent studies in the Eastern Cape have identified the presence of multiple strains in some patients who had not converted in the expected time frame, emphasising the risk of multi-bed wards. Cross-infection results in prolonged patient distress, ongoing blockage of scarce beds and high costs for ongoing treatment. Communal ablutions are also high-risk exposure areas. In order to limit the possibility of cross-infection (multiple infections) between patients, and in line with international best practice, it was recommended that single bed wards with en-suite ablutions were to be strongly preferred. In some cases, however, double and four-bed rooms were accepted due to specific site, cost and client constraints.

The building typology encapsulated in the CSIR initial concept design was for simple, single-storey design solutions with single-loaded³ open-corridors arranged around an open courtyard system. This design strategy allows for the ventilation of rooms directly to the outside and for positioning of openings on two opposite walls, which promotes cross-ventilation by natural means. This allows for dilution of contaminated air in indoor spaces and reduces opportunity for contamination of adjacent areas. Where natural ventilation techniques are inadequate to meet the dilution requirements for acceptable infection control, or where building performance in the particular climatic conditions compromise patient comfort to an unacceptable level, additional technical solutions are indicated. Thus the removal of contaminants from the air via filtration with engineered pressure cascading (ventilation dispersion) and the use of UVGI units (disinfection) in conjunction with suitable air mixing may be engineered either as supplementary technology (mixed mode) or as an alternate technology.

Although there are disadvantages of reliance on natural ventilation for infection control, there are also many advantages such as the low cost of installation, operation and maintenance, the reduced reliance on electricity supply (which is constrained and erratic in some areas) and environmental benefits of reducing reliance on electricity. For natural ventilation to be effective it must already be considered during the early stages of a facility's design development, because it may not be conducive to retrofit a building that was not specifically designed for natural ventilation. When developing the design concept for a naturally ventilated building the following basic steps must be taken:

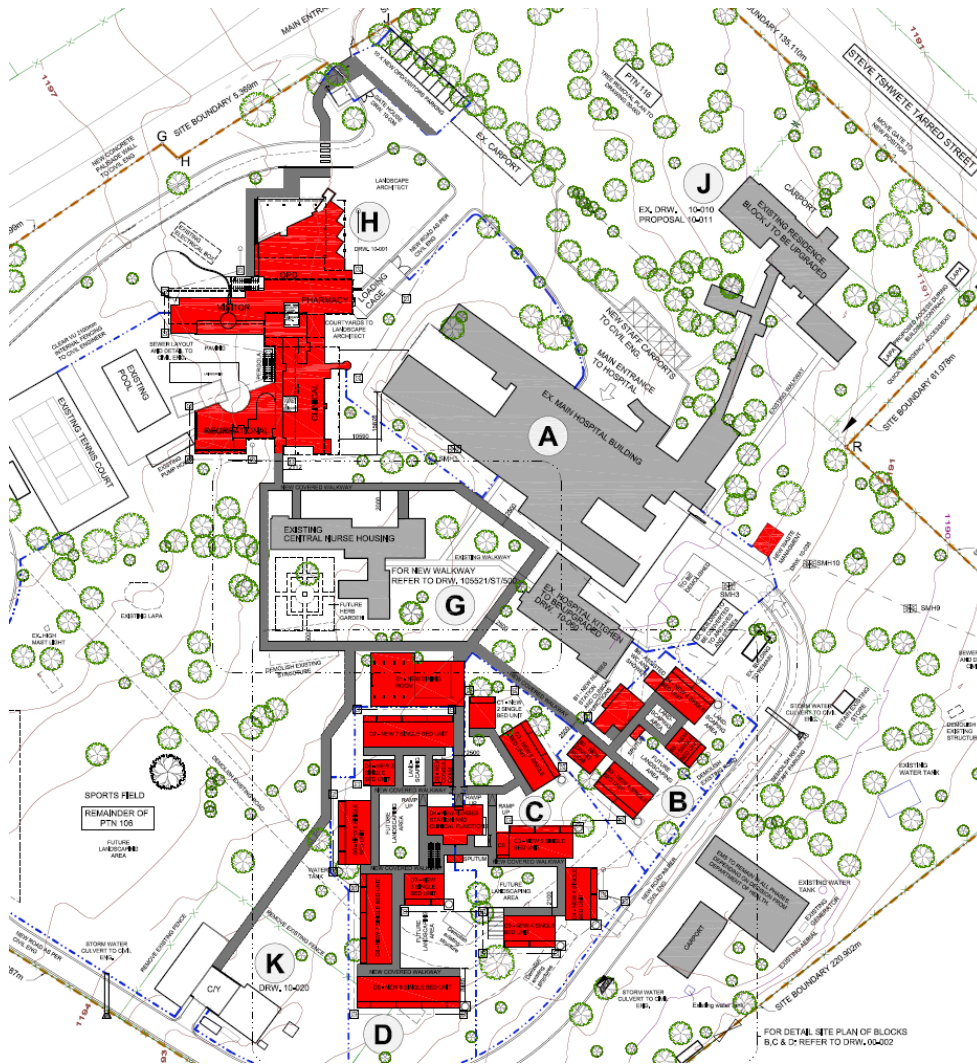
- The desired airflow patterns from inlets to outlets (windows, roof and other ventilators) through the occupied spaces need to be defined. This is related to the form and organisation of the building, use patterns and site configuration. Ventilation systems need to be omnidirectional
- The principle driving forces, which enable the desired airflow pattern and air changes to be achieved, are to be identified. Depending on the building form, wind-driven and/or stack-driven

³ That is, having rooms opening from only one side of access corridors.

strategies can be considered. In a good design the dominating driving forces are in sympathy with the intended flow rate and distribution.

- The size and location of the openings (windows) so that the required flow rates can be delivered under all operating conditions.

In order to provide technical assistance to design teams, the services of the CSIR Building Performance Laboratory⁴ were enlisted to provide decision support for natural ventilation design.



Figures 4 and 5 illustrate in more detail two of the different design solutions developed from the same core set of principles. In figure 4 (Modimolle) sections B (XDR-TB) and C and D (MDR-TB) are made up of a set of clustered accommodation blocks whereas in figure 5 a more unitary approach is adopted.

Figure 4: New phase 1 redevelopment at Modimolle TB hospital, Limpopo showing existing hospital (A), new 12 bed XDR-TB block (B), new 64 bed MDR-TB blocks (C, D) and new out-patient, pharmacy, recreation, rehabilitation and visitors block (H)

⁴ The Building Performance Laboratory is a specialised 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.



Figure 5: New phase 1 redevelopment at Jose Pearson TB Hospital, Eastern Cape showing existing scattered buildings and the new 40-bed XDR-TB block (red)

4. Design modelling and evaluation

Using computational fluid dynamic (CFD) software, a virtual model of four⁵ of the GF facilities were built⁶, in order to simulate, visualise and analyse the ventilation performance of the initial design proposals. The results led to revisions to the design proposals and directly informed both the gross and detailed design development.

The ventilation efficiency of naturally ventilated buildings is dependent on:

- Site topography and latitude
- Building geometry
- Climate zone - wind direction, speed and availability, temperatures, humidity
- Indoor air temperature – which relates to incident solar radiation and thermal performance of building materials

⁵ Jose Pearson, Manguzi, Catherine Booth, and Modimolle

⁶ One of the most critical aspects for building performance testing is the creation of appropriate simulation models. 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 drawings contained far too much geometric information and far too little technical material information. Both Ecotect and Airpak models 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 complex multilayered 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 ($W/m^2.K$) and Admittance ($W/m^2.K$). The interoperability challenge between CFD and CAD is a key barrier to general technology uptake of CFD in the built environment and an R&D opportunity.

- Type and degree of envelope permeability (type of windows and ventilators)
- Interior flow paths and obstructions
- Occupancy (people and equipment)

A key requirement for the study for the set of TB projects was to ensure acceptable levels of performance (air changes per hour) in patient rooms under low wind speeds. If acceptable performance could be achieved, adjusting window opening sections could be used to create comfort conditions at other times during more extreme conditions (wind, rain, temperature). Window opening section types were carefully selected to ensure optimum air flow whilst maintaining weather protection during rain. A key issue was to build in permanent ventilation openings (roof ridge ventilation and under-roof ventilation) in a way that would not be overridden by users. Thermal comfort during cold spells is obtained in one case using underfloor solar water heating and in others with infrared radiant heaters.

4.1. Climate and building performance

The availability of reliable weather or climate data is essential for studies in natural ventilation. Two levels of data are required: general climatic conditions or climate zone to inform the overall design approach and detailed weather files to enable detailed analyses, modelling and fine-tuning of the design. Table 2 below lists the main zones of the South African climate according to the Köppen climatic classification (Kruger, 2004) with the location of the various TB centres.

Table 3: Main groups of the South African climate according to the Köppen climatic classification (Kruger, 2004) with the various TB centres

Köppen climatic classification	Climatic characteristics	Province	TB Hospital or Centre
BW : desert (arid)			
BS : steppe (semi-arid)	High diurnal temperature fluctuations, cold winter nights, summer rains, occasional dust storms – semi-dry	Northern Cape Free State	West End TB Hospital Kopano TB Hospital
Csa : winter rain hot summers			
Csb : winter rain with cool summers	Prolonged wet winter periods, driving rain, occasional strong winds	Western Cape	Brooklyn Chest Hospital
Cwa : summer rain with hot summers	Summer rain usually in short storms with hot summers, low winter night temperatures, generally low wind areas North-west and north-east from Pretoria	Mpumalanga Limpopo North West	Bongani TB Hospital Modimolle TB Hospital Tshepong Hospital
Cwb : summer rain with cool summers			
Cfa : all year rain with hot summers	High humidity, moderate winters	KwaZulu-Natal	Catherine Booth Hospital Manguzi Hospital
Cfb : all year rain with cool summers	Frequent wind, occasional driving rain	Eastern Cape	Jose Pearson TB Hospital Nkqubela TB Hospital

South African climate is characterised by significant variation between zones, in temperature (annual and diurnal variation), altitude, and predominant wind directions and speed. These variations ensure that building performance will vary across sites both in terms of natural ventilation efficacy and in terms of human comfort levels produced. For this reason, a “one size fits all” approach cannot be applied nationally, although regional generic models could be produced.

As climate data are generally only available for major centres in South Africa, data were interpolated for smaller centres and rural areas, and adapted using specialised techniques⁷, for the CFD application. In

⁷ A general building analysis software product such as Ecotect requires hourly data for a year containing temperature, humidity, direct radiation, diffuse radiation, wind strength and direction, cloud cover and rain. To build a complete hourly weather file for an entire year requires 61 320 values in the Ecotect weather file. This is a time-consuming task. In some cases the wind strength and direction data for a year was re-captured to ensure an accurate predictive wind

addition, weather data analysis at a quantified technical level is not required, because weather is inherently changeable. The modelling is undertaken at the extreme conditions, and the assumption made that if the mechanism operates effectively in these conditions, then it will be effective through the range. Figure 6 shows annual and diurnal temperature fluctuations in two of the centres.

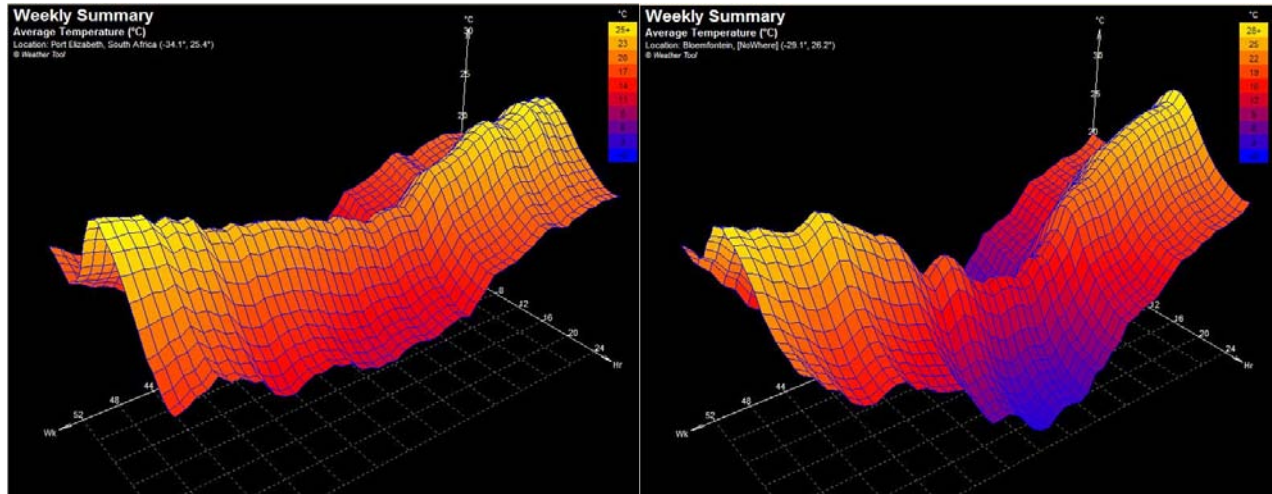


Figure 6: Weather files showing weekly summary temperatures for Port Elizabeth (Jose Pearson - moderate) and Bloemfontein (extreme annual and diurnal fluctuations) closely equivalent to Kimberley (West End Hospital).

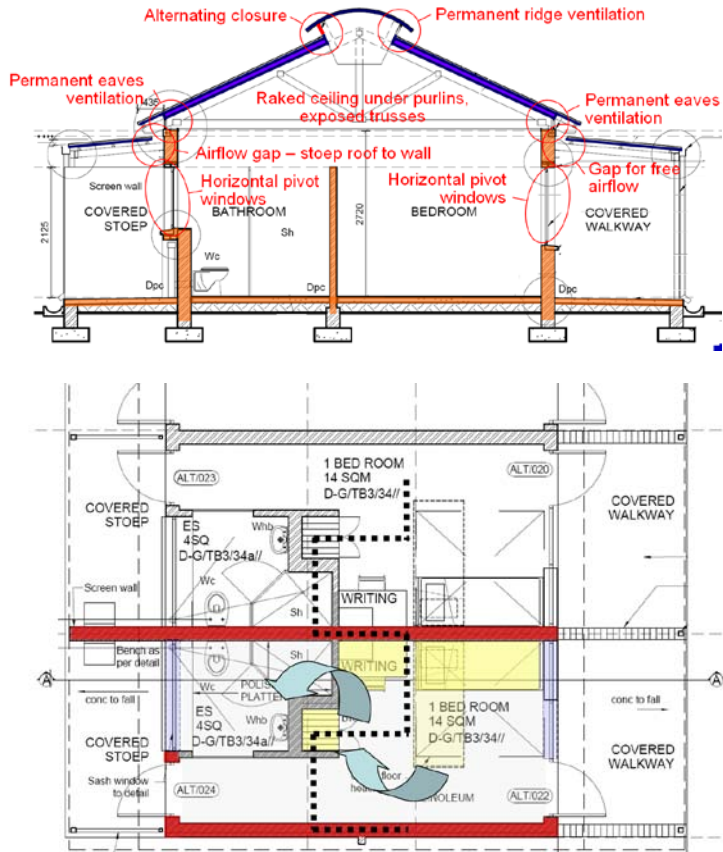
4.2. Natural ventilation simulation using CFD modelling

CFD simulations in the built environment are complex⁸ because the external airflows are highly turbulent⁹. The methodology adopted in CFD modelling is a two-stage approach with an external model (for external airflow) and a zoom-in model. An external model detailing wind direction, strength and turbulence is built to determine boundary conditions. Next, a detailed zoom-in model is constructed, using the boundary condition from the external model as input data.

analysis. The reason for this was that there are discrepancies between datasets with the South African Weather Services (SAWS) data and publications and older CSIR weather publications (Kruger, 2002; Kruger, 2004; van Deventer, 1971)

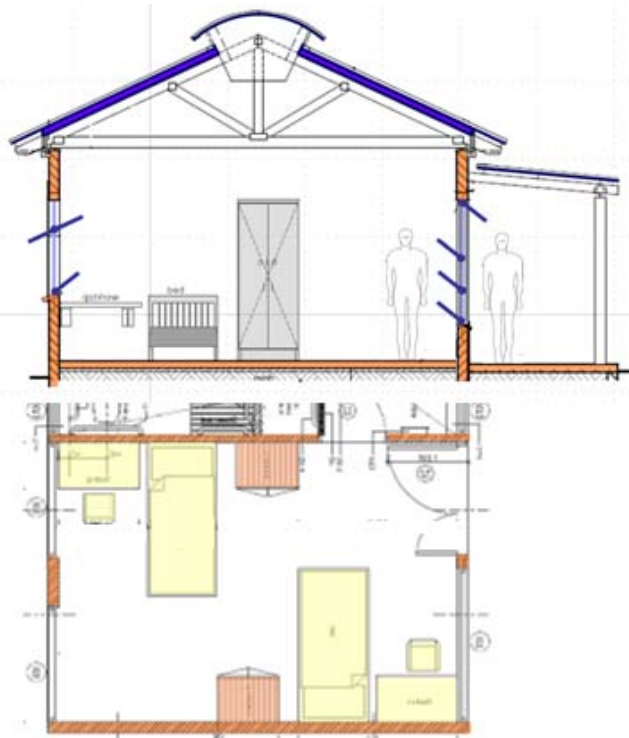
⁸ For example, buildings within an urban environment or on a large site are quite often rotated at many different angles. Ansys Airpak only supports an orthogonal zoom-in model, i.e. a zoom-in cannot be created at any angle. Simulation objects can also only be rotated through right angles, i.e. 90°, 180°, 270° or 360°. This implies that if the original building was rotated then the zoom-in would also have to be created at this inconvenient angle. It is inconvenient for a building application because it is very difficult to build a complex model at an angle. If it is built unrotated there is no way to rotate the model to a non-standard angle. The team devised a mathematical workaround in the Modimolle case study that rotates the various vectors of the boundary conditions for a zoom-in model.

⁹ For example, one of the key challenges currently is to factor the impact of trees and vegetation as a boundary condition into CFD. Currently, the effect of the organic obstructions to air flow is poorly understood. In order to establish accurate air flows for clinics and hospitals in rural areas, effect on the air flow velocity of the surrounding vegetation must be adequately factored into the boundary condition values. During 2009 an extensive set of porous plate experiments were run at the Boundary-Layer Wind-Tunnel (BLWT) facility at the CSIR to determine more accurately what the effect of vegetation would be on air flow.



The initial approach was to provide ventilation openings in the form of horizontal pivot windows, eaves ventilation slots and a roof ridge ventilator (Figure 7). Using CFD, various refinements and alternatives were studied in terms of resultant air velocity, pressure and derivatives such as air changes per hour (ACH) as well as the mean age of air. One of the major changes brought about as a result of the CFD modelling was to have alternate lengths of open and closed sections in the roof ventilator offset on opposite sides of the ridge to ensure that the air will swirl down and into the room before flowing out further down the room (figure 7).

Figure 7: The design approach for natural ventilation – plan and section for Modimolle unit showing ventilation openings and alternating roof ridge openings



Various other window configurations were developed and tested for Catherine Booth Hospital in KwaZulu-Natal (figure 8). Figures 9 and 10 show examples of the simulations undertaken for Catherine Booth Hospital using the illustrated window configurations. The same staggered openings were used for the ridge ventilator and the two figures show sections taken through an inlet and outlet section respectively, illustrating the different velocity vector flow patterns and rates. In all cases the window sizes used and the ratio of openable section to floor area is well in excess of the statutory minimum required by the National Building Regulations. The initial principle of the use of horizontal pivot or a combination of top and bottom-hung windows has been retained to allow maximum airflow and various configurations during adverse weather conditions.

Figure 8: Double room plan and section for Catherine Booth MDR-TB hospital showing different window configuration with horizontal pivot, hopper and top-hung sections

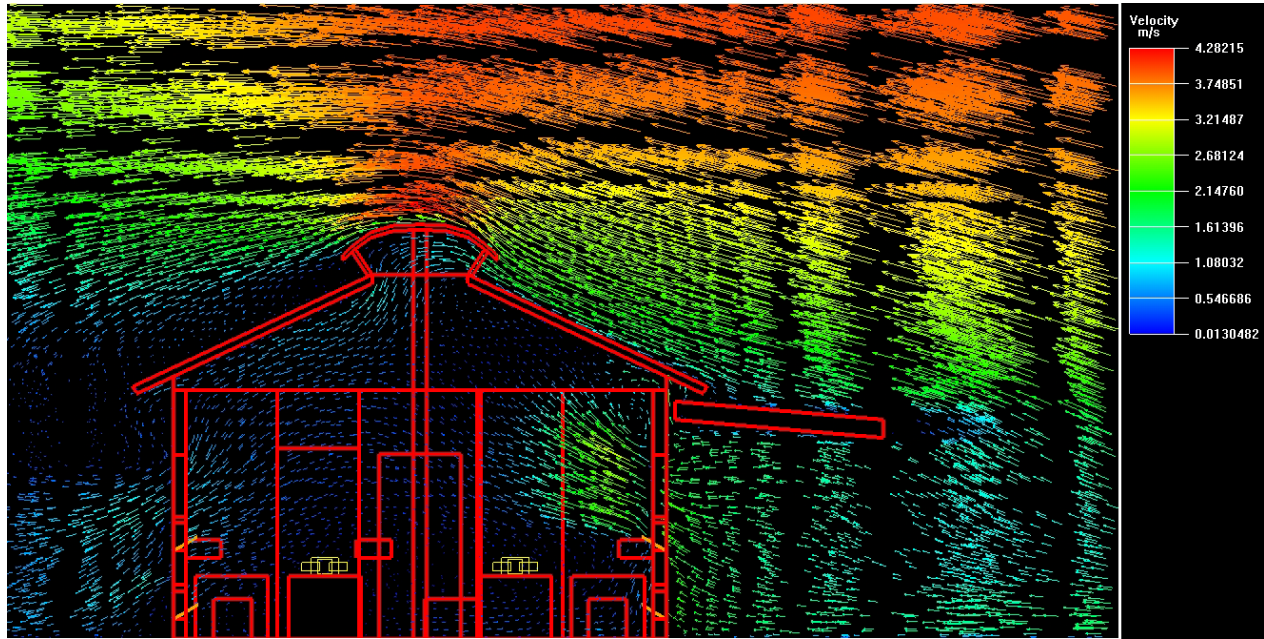


Figure 9: CFD modelling for Catherine Booth – section through windward inlet section of roof showing simulated air flow patterns visualised as velocity vectors. 4m/s external wind speed

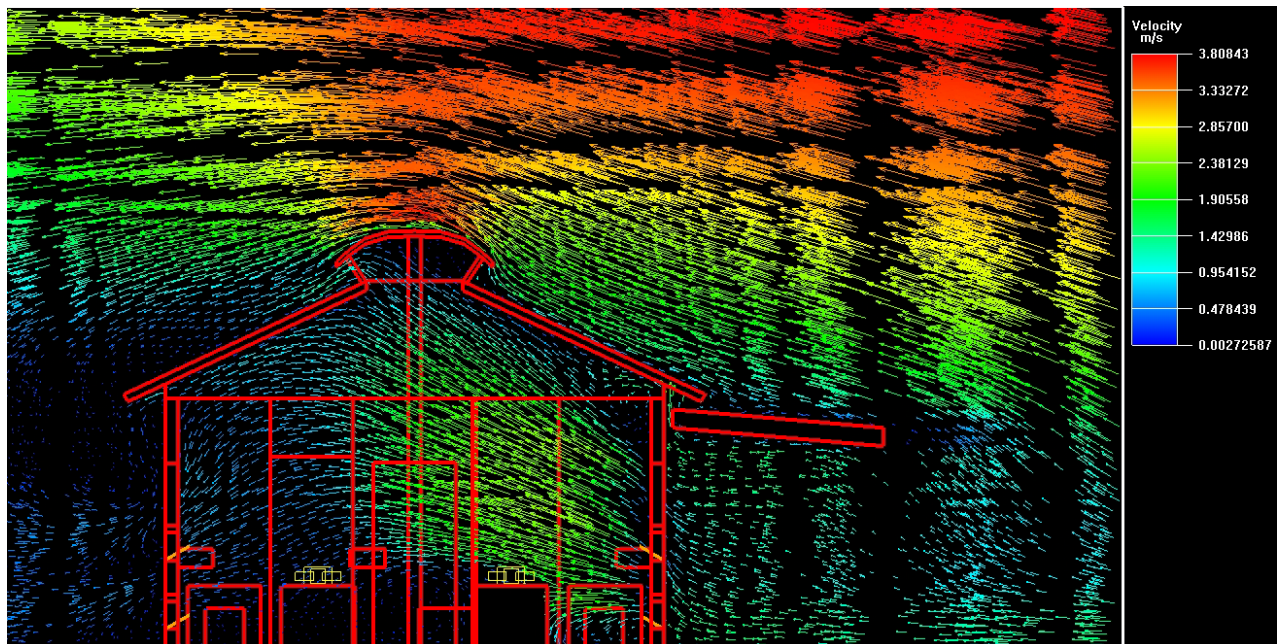


Figure 10: CFD modelling for Catherine Booth – section through leeward outlet section of roof showing simulated air flow patterns visualised as velocity vectors. 4m/s external wind speed. Note that the patients are on opposite sides of the room reducing the chance of directed air from one moving across the other before exhausting

4.3. Validation

Various tests are planned once the units are operational to validate the performance of the units and the predictive CFD modelling. Amongst tests envisaged are CO₂ decay tests to test for air changes achieved.

5. Conclusion

In addition to increasing the available beds for M(X)DR-TB patients by 20% over what is currently available, the GF project has provided the opportunity to develop and review guidelines and standards for new accommodation for M(X)DR-TB patients and to work alongside provincial officials and professional development teams in a capacity development programme developing a pool of expertise for future projects.

The use of CFD modelling has allowed the CSIR team to assess various design options to achieve optimum natural ventilation for user (patient and staff) safety, while working to ensure that comfort conditions are maintained. Various configurations were tested and changes made to the initial design concepts. Further tests will be undertaken once the units are operational to assess the impact of the units in use.

With the new Decentralisation Policy adopted by DoH earlier this year comes the requirement that existing wards in many hospitals across the country will now also need to be used to accommodate drug-resistant TB patients. Infection prevention and control will remain a key requirement in this roll-out programme. The lessons learned through the GF project, together with the Risk Assessment and Management Tool developed by CSIR Built Environment for a parallel research project being undertaken for DoH (funded by CDC), will enable the CSIR to provide valuable input towards assessing the risk and remodelling the required units as necessary to create a safe and secure environment for the treatment of DR-TB.

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