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The Environmental Performance of a Remote-Region Health Clinic Building, Australia, Based on Instrumental Monitoring

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Abstract. Both environmental (e.g., energy use) and human sustainability (occupant wellbeing/productivity) need to be considered in building design and operation. The challenging climatic and socioeconomic conditions in remote regions of Australia mean that achieving sustainability is difficult and costly. Currently, the energy use patterns, thermal performance, and indoor atmospheric quality (IAQ) of remote health clinic buildings are unknown, meaning that there is an information gap in the design and operation of such buildings. This paper reports the results of an investigation into the environmental performance of a clinic in the remote clinic of Numbulwar. Climate variables, energy consumption, and IAQ variables were instrumentally monitored at the clinic from April 2017 to March 2018 at 10-minute intervals, with data uploaded to a cloud database now holding 3 million values. Analyzed temporal variations in the measured variables for the clinic and the relationships between them reveal the performance of the building. The results obtained provide a basis for the formulation of strategic interventions, design guidance, and further investigation, including: (i) the range of indoor atmospheric conditions needs to be narrowed to provide more consistent occupant comfort; (ii) an occupancy profile needs to be developed to determine user behaviours with respect to energy use; (iii) the heat-exhaust/aircon systems need to be reviewed for more efficient use; (iv) the cycling of air, heat, moisture, and pollutants through the building needs to be further investigated; and (v) BIM should be undertaken using the data as input to test future design solutions.

1. Introduction and background

Sustainable building practices have made significant advances in the last two decades [1]. However, a truly sustainable building addresses not only environmental impacts but also human sustainability and well-being. Environmental sustainability is the ability to maintain the qualities of the natural environment, including the processes involved in producing energy, as well as the impact of buildings and human activity on the environment. Human sustainability involves specific strategies and methods for enhancing the well-being and productivity of building occupants/users [2].

Remote parts of Australia are defined based on the physical road distance to the nearest town or service centre. Remote Australia is home to around 500,000 people or 3% of the Australian population. The remote regions of Australia have common systemic problems including persistent social and economic disadvantage and weak infrastructure. These remote-region characteristics when combined with changing climate and different energy futures result in particular challenges faced by remote-region buildings and their occupants with respect to environmental and human sustainability compared with urban areas, including generally harsher climates with greater temperature extremes and much higher electricity costs (up to \$5/kWh versus \$0.25/kWh) [3].



Climatic conditions in the remote regions of Australia are acknowledged to be harsh, characterized by extreme temperatures, wide temperature variation, and high seasonal variation in rainfall. Such conditions pose difficulties for achieving environmentally efficient buildings [4] and for establishing high levels of IAQ for sustaining human comfort and well-being. These challenges are likely to become greater, given projections of climate change (higher temperatures and general declines in precipitation) and energy requirements (increasing demand and higher prices).

Remote Australia is still highly dependent on fossil fuels for transport and for household and public service energy needs. Energy consumption is rising, and the use of air-conditioning will increase with increasing temperatures in inland Australia, which will lead to even higher demand for energy to maintain current lifestyles and to address the changing requirements of an ageing population. Energy prices are likely to continue to rise as the cost of production of fossil fuel increases, and electricity production plants will be obliged to purchase emissions permits under legislation. Renewable energy sources have low uptake in Remote Australia, with barriers including the costs of development and maintenance in remote locations, perceptions, relatively immature technology, and the distance between energy sources and markets [1][5][6].

Remote Australia is served by a network of health clinics and associated staff. Hospitals and clinics need to generate conditions that are conducive to medical treatment and recovery by mitigating the spread of disease and improving occupant comfort, as well as allowing staff to work productively. Indoor atmospheric quality (IAQ) provides a critical foundation for meeting this target. However, strategies to enhance human health and well-being have unfortunately played a minimal role in the evolution of building standards and practices in remote communities. Further, there is a continuing drive to reduce the environmental impact of buildings, particularly with respect to energy use, as well as to reduce operational costs. Therefore, it is imperative that human health and productivity, as well as environmental quality, take centre stage in building design, function, and operation so that buildings can perform better for both people and the environment. This can be achieved through a dedicated focus on evidence-based research and the measurable performance of sustainability metrics.

2. Research purpose and objectives

Climatic conditions impact significantly on a building's ability to provide the necessary conditions for occupant well-being as well as on its environmental efficiency, particularly its energy consumption. Climatic conditions have changed significantly over the last century, and predictions indicate that changes will continue to occur in the near and mid-term futures. Therefore, it is important that climatic and building performance data be available not only to assist in measuring and managing energy use and IAQ in existing health clinics, but also provide a base upon which future clinics can be planned, designed, constructed, and operated. Currently, the Northern Territory Government Department of Health (NTGDoH) has no data regarding environmental sustainability (as measured through energy use) and human sustainability (as measured through IAQ) for its remote health clinics. Such data should be a valuable tool for developing strategic interventions in existing buildings and for indicating sustainable design solutions in new buildings. This study examines the energy use, thermal performance, and IAQ of the Numbulwar health clinic building based on monitored data.

The term "environmental performance" here refers to three aspects: 1. The energy use patterns of the building with particular attention to diurnal–nocturnal and seasonal patterns as well as relationships with other variables. 2. The thermal performance of the building. This covers, in particular, the ability of the building to minimise energy consumption by reducing the need for cooling (and potentially heating, if needed) in the interior of the building. This is a function of the design of the building and the construction materials used, and the extent to which these moderate the external ambient conditions. 3. The IAQ of the building, referring to the properties of the indoor air and the associated comfort and well-being of the building's occupants with respect to these properties. In this study, this covers the temperature and humidity of the air as well as chemical and particulate pollutants. The objectives of the study are:

1. To establish and analyze a database of variables (indicators) measuring aspects of environmental and human sustainability by instrumental monitoring at the Numbulwar clinic;

2. Based on the monitoring and measurement of the chosen indicators, to inform decision-making and strategic interventions in the operation of the Numbulwar health clinic; and
3. To evaluate the Numbulwar clinic data with respect to understanding the operation of other existing health clinics as well as the design and construction of future health clinics.

3. Method and data

The health clinic building is located in Numbulwar in the Northern Territory (fig. 1) and was built in early 2017. The clinic (fig. 2) has 22 rooms in total and has a floor area of around 300 m², serving around 2000 people in Numbulwar. Numbulwar has a long-term average maximum temperature of 28.8°C, a dry winter season (May–September) with humidity of 20%–50% and temperature of 15–33°C, and a wet summer season (October–April) with humidity of 30%–95% and temperature of 22–35°C.

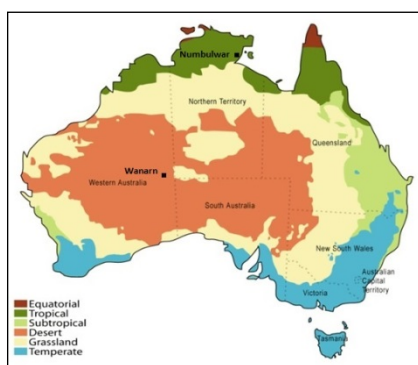


Figure 1. Political states and climatic zones of Australia, and the location of Numbulwar.



Figure 2. Numbulwar clinic building.

This study involved a quantitative empirical approach, with monitoring instrumentation being installed both within and outside the clinic building to continuously measure energy use, IAQ data, and external climatic data for a 12-month period. Analysis of these quantitative data provides an account of the temporal variation in the selected environmental and human sustainability indicators as well as of the relationships between the indicators.

The clinic building had been constructed by 1 April 2017 but was unoccupied and non-operational prior to mid-September 2017. In mid-September, the clinic started its operational phase with staff and equipment being used for the usual duties and functions performed by a health clinic. As the measurements made cover both the pre-occupancy and post-occupancy phases of the Numbulwar clinic building, the data from each phase contribute different insights into the environmental and human sustainability of the building, as well as indicating comparative differences between the two phases.

A suite of 24-hour electronic monitoring equipment was set up to record climatic, energy consumption, and IAQ data for the Numbulwar clinic for a period of 12 months. The monitoring equipment was installed in late March 2017. The monitoring devices were installed in various rooms/corridors inside the building as well as inside the ceiling/roof-space cavity. Devices were also installed on the eastern and northern external walls of the building. An energy consumption meter was installed on the switchboard. Once installed, data were uploaded continuously at 10-minute intervals via the Telstra network to a cloud-based platform, from which data could be accessed via a secure portal either live or as downloads. The following data were collected from April 2017 to 31 March 2018: Climate (external) variables – temperature and humidity; total building energy consumption; and IAQ variables – temperature, humidity, and airborne chemicals and particulates.

The 12-month database contains around 2,880,000 values. The database was first inspected thoroughly for data consistency and quality. A number of periods were discovered during which data were not recorded because of transmittance or other disruption (accounting for <0.1% of the total data).

4. Selected results and findings

Selected graphs (with data frequency of 10 mins) are presented that summarize some of the key variables and data trends for the clinic building, with accompanying results, interpretations, and findings.

4.1. Local climate

External temperature and humidity values reflect the tropical location of the Numbulwar clinic. Day-time temperatures generally exceeded 35 °C and sometimes 40 °C (fig. 3). Maximum temperature variations were observed in April–May and December–March. Minimum (night-time) temperatures were most variable between April and September (17.5–28 °C) and more stable (~25 °C) between October and March. Monthly mean temperatures were lower from June to September compared with the other months, with the range being 26.7 °C in June to 31.0 °C in December. A typical diurnal cycle during December sees temperature starting to increase from its night-time level at about 06:00, reaching its maximum typically between 11:30 and 13:00, from which time it slowly decreases during the later afternoon, evening, and night-time to reach a short stasis period at ~05:00.

Humidity values varied from 25.9% to 97.5% during the 12-month study period (fig. 4). Maximum humidity levels are closely controlled by temperature, with maximum humidity values of 45% at 40 °C and 95% at 27 °C. On a diurnal scale, humidity was highest during the night-time. In December, for example, humidity peaked at ~04:30–06:00 (e.g., 90%) and then reduced to reach a minimum at ~11:30 to 13:00 (e.g., 35%), following which it rose through the afternoon, evening, and night to reach its next peak at the same time the next morning.

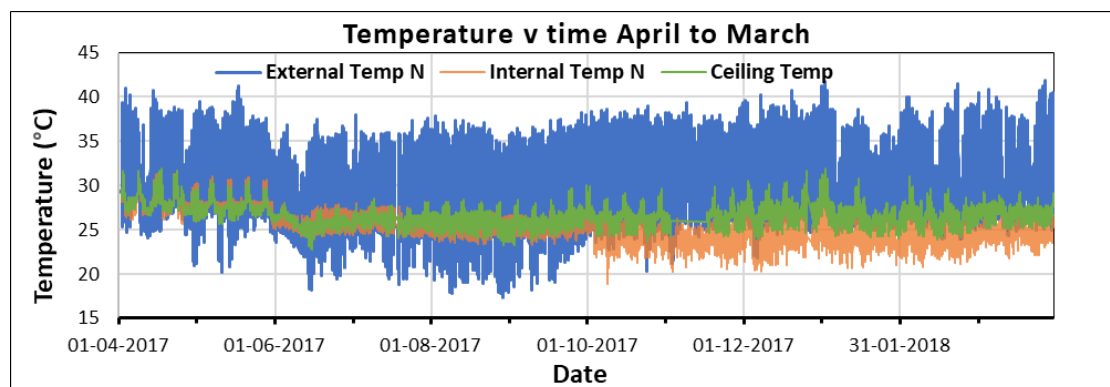


Figure 3. Temporal variation in external and internal temperatures (northern part of the building) and in ceiling-space temperature of the clinic from 1 April 2017 to 31 March 2018.

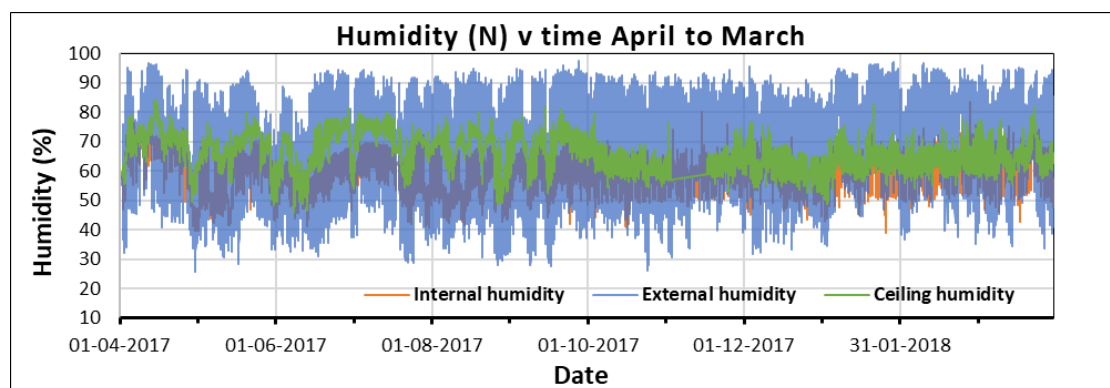


Figure 4. Temporal variations in external and internal humidity (northern part of the building) and ceiling/roof-space humidity for the clinic 1 April 2017 to 31 March 2018.

4.2. Energy consumption of the building

As a result of the external temperature variation, energy consumptions associated with air-conditioning are higher during the months of October to May and lower from June to September (fig. 5). Day-time temperatures have a major influence on the energy consumption of HVAC units, with higher external temperatures causing higher energy consumptions because of the greater differential between indoor and outdoor temperature. This is shown, for example, by the higher energy consumptions recorded for higher outside temperatures in maintaining a constant indoor temperature (fig. 6).

Despite the broad relationships observed between energy consumption, external temperature, and internal temperature, there is a large amount of scatter in the data (fig. 6). The very wide range of external temperatures associated with the corresponding internal temperature range for the same energy consumption level, and the very wide range of energy consumptions associated with maintaining the internal temperature at 21–25.5 °C, suggest that there is potential for efficiencies to be made in the operation of the HVAC and heat exhaust systems of the clinic building and for an investigation to be made into human activity and behaviour in the clinic regarding the generation of heat and moisture.

From mid-September, the clinic building became occupied and operational, with total daily energy consumption increasing from that point. September was a transitional month for the clinic, marking the start of occupancy/operation and the associated adjustments in building mechanical and electrical systems, including HVAC. Therefore, the period October–March best represents normal occupancy and building use. For this period, for energy consumptions of <8 kWh per hour (at which level it is assumed that HVAC is not running), there is a horizontal band of data for which external temperatures up to ~40 °C are associated with internal temperatures of 22.5–27 °C (fig. 6). The horizontal band represents times before ~09:30 and after 15:00 during some weekends when a reasonable internal temperature range was maintained in the building without the use of HVAC. On these weekends, the clinic was open for shorter times and HVAC was being run only between ~09:30 and 15:00.

The October–March data show a positively sloped band of external temperature data, extending from energy consumptions of ~18 kWh per hour and temperatures of ~25 °C to consumptions of ~28 kWh per hour and temperatures of ~40 °C (fig. 6). This band covers a range of internal temperatures from ~21 to ~27 °C with most between 21 and 25.5 °C. Assuming that the variation in energy consumption above 8 kWh is due mainly to HVAC operation, then for every 3 °C rise in the external temperature, an additional 2 kWh per hour is needed to maintain the observed range in internal temperature.

Data scatter means that there is a very broad range of external temperatures associated with the corresponding internal temperature range for the same energy consumption level. For example, high energy consumptions of ~25 kWh per hour occur for external temperatures of between 25 and 40 °C. In addition, energy consumptions of 10–55 kWh per hour are associated with maintaining the internal temperature at 21–25.5 °C, although most of the data lie within the 15–35 kWh range. The scatter may be due to inefficiencies in the HVAC system or variations in occupant behaviour and equipment use.

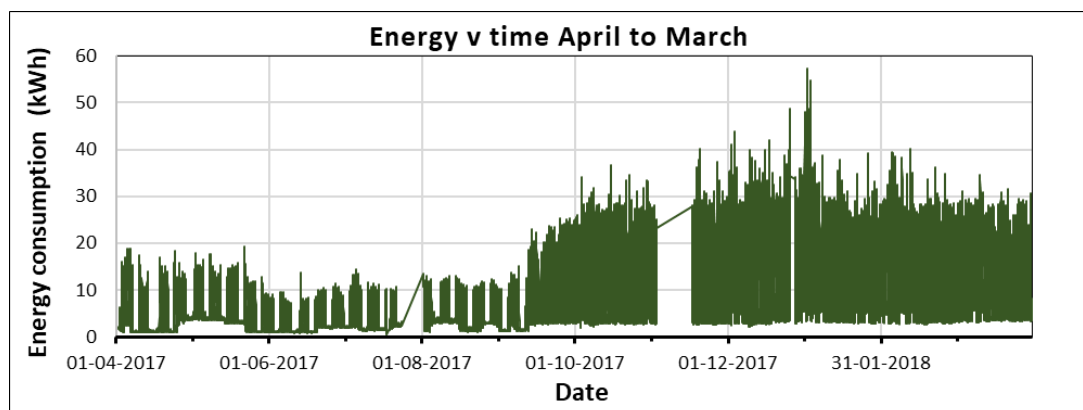


Figure 5. Clinic energy consumption for the period 1 April 2017 to 31 March 2018 (kWh measured over hourly intervals).

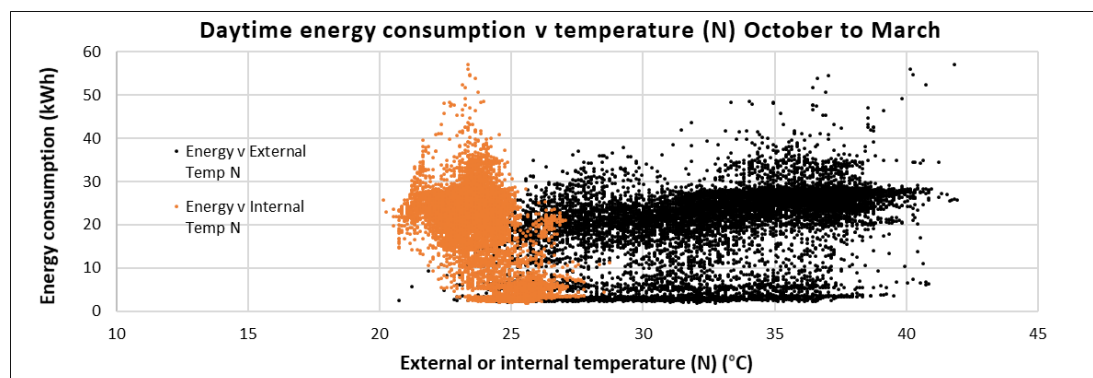


Figure 6. Clinic energy consumption versus external and internal temperature for the northern side of the building for 1 October 2017 to 31 March 2018 (energy in kWh measured over hourly intervals).

4.3. Thermal performance of the building

Inferences about the thermal performance of the building and the effectiveness of the building skin can be made by investigating temperature characteristics when the building is unoccupied, the HVAC system is not running, and the weather is hot and sunny. The energy use pattern during the operational period from mid-September onwards indicates that the HVAC system was running every day during the day-time. However, the period prior to mid-September, while the building was unoccupied and non-operational, contained several weekends where HVAC was clearly not running. For one such weekend in June (fig. 7), the 24-hour variation in external temperature of $\sim 10^\circ\text{C}$ is reflected by a variation in ceiling/roof-space temperature of $\sim 1^\circ\text{C}$ (with the peak temperature lagged by ~ 3.5 hours) and by a variation in indoor temperature of $\sim 2^\circ\text{C}$ (peak temperature lagged by ~ 4 hours). For a similar period in early September, the variation in external temperature is $\sim 16^\circ\text{C}$, in ceiling/roof-space temperature is $\sim 3.5^\circ\text{C}$, and in internal room temperature is $\sim 2.5^\circ\text{C}$. The peak temperature lag time is the same as the June data, ~ 3.5 – 4 hours for both ceiling/roof-space temperature and internal room temperature.

On the above basis, the building skin and thermal envelope of the Numbulwar clinic seem effective at dampening solar gain and conduction of heat into the building from the outside. The ceiling/roof-space performs particularly well, given that it is the part of the building that is most exposed to direct sunlight. The daily increase in external temperature from its night-time value is typically $\sim 15^\circ\text{C}$ for most of the year, and the typical rise in building indoor temperature (unoccupied, no HVAC) during the day-time is determined to be $\sim 2^\circ\text{C}$ and the rise in ceiling/roof-space temperature ~ 2.5 – 3.5°C .

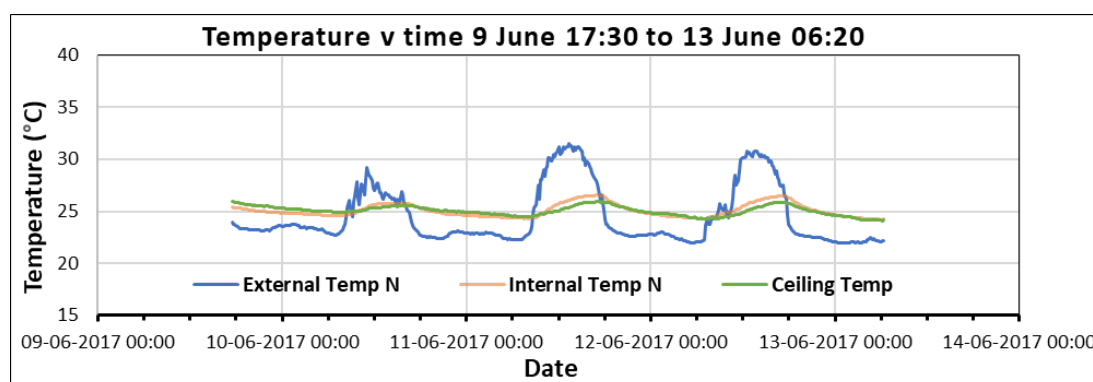


Figure 7. Variation in external and internal temperature (northern part of building) and in ceiling/roof-space temperature for the clinic for 9–13 June, during which the building was unoccupied and no air-conditioning or other mechanical/electrical systems were operating (apart from fridges/freezers and night lighting).

4.4. Indoor atmospheric quality of the building

4.4.1. Internal temperature. The internal (indoor) temperature in the northern part of the building shows three distinct periods between April 2017 and March 2018 (fig. 3). During April and May, the temperature was quite variable, ranging between 26 and 32 °C with a mean of 28.0 °C. This is interpreted as representing testing of the HVAC system or minor works occurring in the building. At the beginning of June, the internal temperature dropped, probably as a result of a manual adjustment to the air-conditioning thermostat. From 3 October, the internal temperature dropped and became more variable, ranging between 19 and 28 °C from then until the end of March, although more generally between 20.5 and 26.5 °C, and with a mean of 24.2 °C. This drop is presumed to be an adjustment to the thermostat control of the air-conditioning system at the beginning of the occupied/operational period of the clinic.

Consistent temperature differences exist between indoor locations through the operational months of October–March. In March, for example, the day-time temperatures in the waiting room were ~2 °C cooler than those in the northern consulting room, which in turn were ~2.5 °C cooler than the corridor area in the central-west part of the building. This may indicate variable airflows, variable distances from HVAC vents, and/or zoned control of airconditioning throughout the building.

The indoor air temperature range that meets ASHRAE 55:2013 “Thermal Environmental Conditions for Human Occupancy” standards is 21.0 to 24.9 °C (the range in which 90% of occupants feel fairly comfortable). For day-time (06:00 to 18:00) hours, the clinic’s internal temperature for October–March varied between 20.1 and 28.7 °C but more usually between 21.0 and 26.5 °C, with a mean of 23.4 °C. The minimum and mean temperatures appear to be acceptable, but ~10% of the data exceed 24.9 °C.

4.4.2. Internal humidity. The internal humidity in the northern part of the building varied from 39% to 83% between April 2017 and March 2018 (fig. 4). The humidity behaviour from late September to the end of March (building occupied) is characterized by high shorter-term variability but with fairly stable moving-mean-value trends. Day-time data for October–March (fig. 8) show that internal temperatures of ~21 °C are associated with humidity values of ~65% to 70%. The range in humidity for a particular temperature increases with increasing temperature until a temperature of ~23 °C is reached, with the lower bound for humidity decreasing from ~65% to ~40% as temperature increases from ~21 °C to ~25 °C. Temperatures of 22–26 °C are associated with a wide humidity range, from 40% to 75%. Day-time humidity for October–March ranged mainly from 45% to 75% (mean 59.9%).

Temperature and humidity are important IAQ metrics of a building as they largely determine the physical comfort of an occupant. It is generally regarded that the optimum humidity range for human comfort is 35%–65%, which, if applied to the Numbulwar clinic, would mean that around 15% of the day-time humidity values are too high. ASHRAE thermal environmental conditions for human occupancy show that if the humidity is 60%, then a suitable temperature range is 23–25.5 °C and if it is 30% then a suitable temperature range is 24.5–28 °C. The clinic’s temperature–humidity value distribution includes this former value range (fig. 8) but has considerable amounts of data outside it.

5. Conclusion

This study monitored external climate variables, energy consumption, and IAQ variables for a health clinic building in the remote community of Numbulwar, producing ~2.9 million data over a 12-month period. It is the first case where a suite of sustainability variables have been measured over such a time-frame for a healthcare facility in Australia.

An analysis of temporal variations in the monitored data, including at the diurnal and seasonal scales, as well as differences between the non-operational and operational phases of the clinic, has allowed inferences to be made regarding building energy use patterns, thermal performance, and IAQ. Relationships between climatic variables, energy consumption, and IAQ metrics highlight where interventions might be made to optimise the building systems as well as showing where further investigation would be most beneficial.

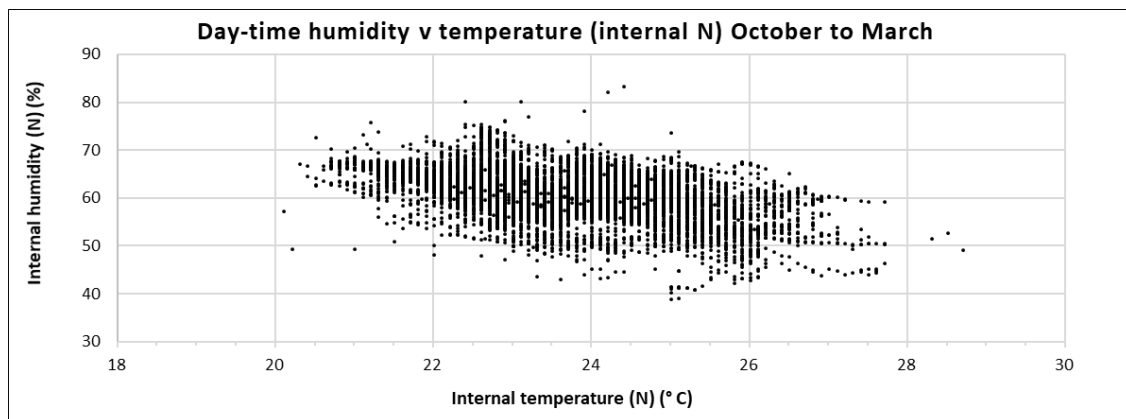


Figure 8. Internal humidity versus internal temperature during the day-time for 1 October 2017 to 31 March 2018.

Strategic interventions and further investigation include: (i) the range of indoor atmospheric conditions needs to be narrowed to provide more consistent occupant comfort; (ii) an occupancy profile needs to be developed to determine user behaviours with respect to energy use and other aspects (e.g., [7]; (iii) the heat exhaust and air conditioning systems need to be reviewed for more efficient use; (iv) the cycling of air, heat, moisture, and possible pollutants through the building needs to be further investigated; and (v) BIM should be undertaken using the data as input to test design solutions and discover which design features of the current clinic are contributing most to building performance (e.g., [8]). As part of a wider ongoing investigation, these results will help to develop key clinic building performance indicators, inform improvements in the energy-use efficiency, thermal performance, and IAQ of remote clinics, and optimize future building design solutions buildings via BIM simulations to optimize sustainability with respect to climate, environmental performance, and occupant well-being.

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