Chapter 12
Implications of a Natural Ventilation Retrofit of an Office Building

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12.1 Introduction

> Learn to look after your staff first and the rest will follow. Richard Branson

The relationship between the physical office environment and employee satisfaction has received global attention as a critical aspect contributing to business success (Budie et al., 2018). Raising satisfaction with the physical work environment has become a major corporate real estate strategy (Budie et al., 2018). Work environment satisfaction is the extent to which the physical work environment meets the needs of office users (Kim & de Dear, 2013). However, business parks are often poorly designed in terms of energy efficiency, indoor air quality and occupant thermal comfort (Khatami, 2014). In addition, the affordability of mechanical ventilation systems resulted in a decline of vernacular and passive design strategies used in office buildings; this has resulted in the increase of worldwide installed capacity of air-conditioning systems from below 4000 GW in 1990 to over 11,000 GW in 2016 (Asfour, 2017). Energy consumption for indoor space cooling is anticipated to triple until 2050 (Braungardt et al., 2019), whilst the built environment sector contributes up to 30% of global annual greenhouse gas emissions and consumes up to 40% of all energy (Zhai & Helman, 2019; Geng et al., 2019).

Natural ventilation has been recognised as one of the most promising sustainable strategies to reduce building energy consumption, improve thermal comfort and maintain a healthy indoor environment (Tong et al., 2016; Wang, 2017). However, many local modern office buildings were constructed in the absence of passive design principles when research shows that most people favour natural ventilation and openable windows (Carrilho & Linden, 2016). In addition, they tend to show

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increased thermal tolerance when occupying naturally ventilated buildings. Natural ventilation retrofits provide a possible solution. However, the perceived negative aspects to natural ventilation, namely, external ambient air pollution and increased internal particulate matter counts, need to be carefully considered in the decision-making process (Tong et al., 2016). However, data to inform this decision-making is limited, and therefore the aim of this research is to explore the impact a natural ventilation retrofit has on indoor air quality, occupant thermal comfort and ventilation in a commercial office building located in Port Elizabeth, South Africa.

12.2 Indoor Air Quality

'Indoor air quality or IAQ' is what we experience as the temperature, humidity, ventilation and chemical or biological contaminants of the air inside our buildings (Brown, 2019). Many people spend 90% of their day indoors where air pollution can be two to five times more polluted than levels outside (Marta et al., 2017). Furthermore, building environments are exposed to all kinds of textiles, equipment, paper, cleaning products and maintenance activities producing contaminants that leave indoor air very different from 'fresh outside air' (Brown, 2019). The health risks from exposure to indoor air pollution may therefore be higher than those related to outdoor pollution (Cincinelli & Martellini, 2017). In particular, poor indoor air quality can be dangerous to vulnerable groups such as children, young adults, the elderly or those suffering chronic respiratory and/or cardiovascular diseases (Cincinelli & Martellini, 2017), the same groups that have been most impacted by the COVID-19 pandemic (NCIRD, 2020). IAQ has thus received increasing attention from the international scientific community, political institutions and environmental governance as a means for improving the comfort, health and well-being of building occupants (Abouleish, 2020).

12.3 Indoor Carbon Dioxide

Carbon dioxide (CO_2) is a colourless, tasteless, odourless and non-flammable gas that is heavier than air and may accumulate at lower spaces, causing a deficiency of oxygen (Azuma et al., 2018). The normal outdoor CO_2 concentrations are approximately 380 ppm, although in urban areas these have been reported to be as high as 500 ppm because of the increased human activity (Azuma et al., 2018). The main source of CO_2 in the non-industrial indoor environment is human metabolism (Park et al., 2019). The indoor CO_2 concentration is an indicator of indoor air quality acceptability, air flow exchange suitability and whether there is enough fresh air within indoor spaces (Park et al., 2019). The average indoor CO_2 concentration ranges from 800 to 1000 ppm, with an upper limit of 1000 ppm for CO_2 concentrations in commercial buildings (Park et al., 2019). Ventilation with ambient air is often used for reducing indoor CO_2 concentration. Research has also indicated that for every 100 ppm decrease in the differential between indoor and outdoor carbon dioxide concentration (dCO_2), office workers experienced fewer SBS symptoms, including 60% fewer reports of sore throat and 70% fewer reports of symptoms of wheezing (Park et al., 2019). They further report that CO_2 affects decision-making at thresholds of 600 ppm, which is below the normally accepted comfort range of 1000 ppm (Park et al., 2019). A study in human subjects stated that inhalation exposure to 1000 ppm CO_2 for a short term caused marked variations in respiratory movement amplitude, peripheral blood flow increases and the cerebral cortex functional state (Azuma et al., 2018).

12.4 Sick Building Syndrome (SBS)

Sick building syndrome presents symptomatically as the complex spectrum of ill health complaints, such as mucous membrane irritation (rhinorrhoea, nasal congestion, sore throat, eye irritation), asthma symptoms (chest tightness, wheezing), neurotoxic effects (a headache, fatigue, irritability), gastrointestinal disturbance, skin dryness and sensitivity to odours (Nag, 2019). These symptoms may present among occupants in office buildings, schools, public buildings, hospitals and recreational facilities (Nag, 2019). Building-related sicknesses have been observed as being pervasive in modern high-rise buildings (Nag, 2019). These buildings are designed to be airtight for energy-saving. Subsequently, the windows remain sealed, depriving the building of natural ventilation and daylighting, and HVAC systems recirculate the air in the building, with minimal replacement of fresh air (Nag, 2019). Concerns about human health due to deteriorating indoor environmental quality are gradually increasing with a public outcry among the building occupants as well as challenging lawsuits (Nag, 2019). Typically, maintaining allowable IAQ in office buildings depends on effective ventilation systems in operation. Ineffective or inadequate ventilation systems result in inefficient removal of pollutants from indoor air and display of SBS signs among the occupants (Nag, 2019).

12.5 Natural Ventilation

Natural ventilation essentially describes the air movement created by naturally occurring pressure differences; this pressure difference can be created either by wind or by temperature differences (Alatala, 2016). Proper utilisation of natural ventilation can provide large ventilation rates without the consumption of energy (Wang & Zhai, 2018). As natural ventilation is driven by wind or buoyancy, the naturally ventilated building form includes wind-driven ventilation form, buoyancy-driven ventilation form and the combination of these two. When wind hits a building, positive pressure is created on the windward side and negative pressure on the leeward side of the building (Alatala, 2016), forcing air into the building from the windward side and out from the leeward side, creating cross-ventilation through the building. Natural ventilation is an increasingly popular green-building technology that has proven to be an effective solution to lower building cooling energy and to improve indoor air quality in various climates and types of buildings (Chen et al., 2019).

12.6 Hybrid Ventilation Systems

Ventilation has been shown to play a critical role in improving indoor environments (Meng et al., 2019). Hybrid ventilation is an effective means of minimising ventilation energy and improving indoor climate. It has been found that air-conditioners are often operated for 6–12 h per day, consuming electricity at a rate of 40–45 kWh/m^2 (Weerasuriya et al., 2019). In buildings with hybrid ventilation systems, transition spaces such as corridors, with motorised inlets, have more flexible thermal comfort limits than office spaces and can thus be used to bring in cooler outdoor air increasing cooling energy savings (Yuan et al., 2018). In addition to providing thermal comfort, natural ventilation has the advantage of improving indoor air quality, reducing energy consumption in buildings and eliminating what is known as the ‘sick building syndrome’. From an economics perspective, natural ventilation can reduce a building’s capital cost by about 10–50%, compared to an air-conditioned building of similar dimensions (Weerasuriya et al., 2019). A building’s potential for natural ventilation not only depends on its dimensions and architectural features but also relates to climatic (e.g. wind speed, direction, outdoor temperature, solar radiation) characteristics of the neighbourhood (e.g. geometry and orientation of buildings) and the behaviours of residents (Weerasuriya et al., 2019).

12.7 Research Methodology

Two quantitative research designs were used in this research project. First, an experimental design was used to determine the change in indoor air quality before and after the building’s existing non-openable windows were retrofitted into openable windows. Indoor air quality was measured using a medical-grade indoor air quality device, the AirVisual Node by IQAir. Second, a survey design was used to conduct a pre- and post-survey of sick building syndrome symptoms experienced by employees. The survey was conducted before and after the natural ventilation retrofit. The experimental and survey design allowed this research to correlate the impact openable windows had on indoor air quality and subsequently the impact the change in indoor air quality had on occupant satisfaction and well-being.

12.8 Building Type and Location

The building selected for this research represents typical modern open-planned office buildings in Port Elizabeth, South Africa. The office building selected is currently and has been occupied by an engineering consulting firm since 2009. The building is located along a main road (Fig. 12.1) and had 22 office users during the research period. The office space before the natural ventilation retrofit was mechanically ventilated only. The maintenance of the mechanical ventilation was subcontracted to a specialist firm and to the knowledge of the researcher was maintained regularly. The indoor levels of particulate matter reflect a maintained mechanical ventilation system as office particulate concentrations during the mechanically ventilated office period reached a maximum of 13 μ/m^3.

Figure 12.2 illustrates a street view of the office building. The windows depicted are non-openable. Figures 12.3 and 12.4 illustrate the before and after the existing windows were retrofitted. The existing non-openable aluminium casement window was retrofitted into an openable window. The retrofit took 1 day; ten windows were retrofitted at a cost of R20,000.00 (£950.00). The air quality device was located at a height of 1.6 m and was placed centrally within the office. The manufacture of the air quality monitor states valid measurements for an indoor space of up to 100 m^2, and the research area was 80 m^2 (Chloe, 2020).

Fig. 12.1 Selected office building

Fig. 12.2 Street view

Fig. 12.3 Before retrofit

12.9 Research Method

The indoor air quality device was first placed in the office on the 18th of June 2019. From 18 June to 14 August 2019 (8 weeks), the device captured air quality data for the period prior to the natural ventilation retrofit. During this time, the pre-SBS survey was circulated among office users. The existing windows were retrofitted on the 15th of August, and indoor air quality data for the post-natural ventilation retrofit period commenced. The indoor air quality device captured data for 5 weeks after

Fig. 12.4 After retrofit

Table 12.1 Overview of indoor air quality metrics

Indoor air quality results				
Mechanical ventilation		Hybrid ventilation		
IAQ metric	Mean	IAQ metric	Mean	Change %
PM2.5 (μg/m^3)	2.89	PM2.5 (μg/m^3)	2.23	−23
PM10 (μg/m^3)	4.03	PM10 (μg/m^3)	3.31	−18
Carbon dioxide (ppm)	685.31	Carbon dioxide (ppm)	643.51	−6
Temperature (Celsius)	22.0	Temperature (Celsius)	22.2	+1
Humidity (RH%)	51.22	Humidity (RH%)	51.16	−0.1

the retrofit, during which the employees had complete control over the openable windows. At the end of the 5-week post-retrofit period, the post-SBS survey was circulated among the office users.

12.10 Research Results: Indoor Air Quality

Table 12.1 is a summary of the indoor air quality metrics recorded by the IAQ device. The mean score for each IAQ parameter was calculated for both mechanical and hybrid ventilation. The improvement in IAQ metrics is displayed by the change percentage column. The most notable improvements are reflected by the 23% reduction in PM2.5, the 18% reduction in PM10 and the 6% reduction in carbon dioxide concentrations.

Table 12.2 Carbon dioxide

Office hours in which CO_2 level is >1000 pm	
Before operable windows	36 office hours
After operable windows	0 office hours
Comment	CO_2 levels exceeded 1000 ppm for 8% of total measured office hours

12.11 Research Results: Carbon Dioxide

The analysis of the 14-week real-time data showed in Table 12.2 revealed that the pre-operable window period had 12 incidents in which office carbon dioxide levels exceeded 1000 ppm. The office carbon dioxide level exceeded 1000 ppm for a total of 36 h. On average, office carbon dioxide levels would exceed 1000 ppm twice to three times a week.

Once the operable windows were in use, the office carbon dioxide level did not exceed 1000 ppm for the remainder of the experiment. Operable windows, controlled by employees, effectively reduced >1000 ppm carbon dioxide incidents to 0.

12.12 Research Results: SBS Survey

The sick building syndrome (SBS) survey was conducted using a 5-point Likert scale design. A mean score was calculated for each symptom. The symptoms were then ranked, and the pre- and post-survey results were tabled and compared.

The pre-openable window sick building syndrome questionnaire indicated that the top three symptoms experienced by employees are tiredness, difficulty/poor concentration and nasal congestion. The pre-openable window SBS survey results formed the benchmark to which the post-openable SBS survey was compared against. The impact openable windows had on SBS symptoms experienced by employees is highlighted by the following reduction in the mean scores of the top three SBS symptoms identified by the pre-openable window SBS survey:

Tiredness—18.25% improvement

Difficulty/poor concentration—20.80% improvement

Blocked or stuffy nose—25.82% improvement

Table 12.3 provides an overview of the mean score for SBS symptoms experienced by employees before and after the natural ventilation retrofit. There was a reduction in mean score across almost all the SBS symptoms experience by employees. Notable findings include a reduction in 'dry throat' by 35%, 'runny nose' by 28% and watery eyes by 29%.

Table 12.3 SBS survey results

SBS pre- and post-survey results				
		Mean		
No.	SBS symptoms	Pre	Post	Change %
1	Tiredness	3.89	3.18	−18
2	Difficulty/poor concentration	3.22	2.55	−21
3	Blocked or stuffy nose	3.06	2.27	−26
4	Watery eyes	3.05	2.18	−29
5	Sensitivity to odours	2.95	2.18	−26
6	Sneezing	2.78	2.64	−5
7	Runny nose	2.78	2	−28
8	Dry throat	2.78	1.82	−35
9	Headache	2.68	2.36	−12
10	Coughing	2.67	2.18	−18
11	Dryness and irritation of the skin	2.65	2	−25
12	Dizziness	1.84	1.9	3
13	A sensation of difficulty in breathing	1.78	1.45	−19
14	Tightness of the chest	1.78	1.55	−13

12.13 Discussion

The US Environmental Protection Agency stated that indoor PM10 concentrations should not exceed 150 (μg/m^3) and PM2.5 should not exceed 35 (μg/m^3). The office PM2.5 and PM10 concentrations are significantly lower than the regulations provided by the EPA. However, the natural ventilation retrofit notably contributed to a further reduction of office PM2.5 and PM10 concentrations. The increased ventilation provided by the natural ventilation retrofit contributed significantly to improved indoor office air quality by improving ventilation and introducing clean outdoor air. According to Zhai et al. (2019), it has been found that sick building syndrome (SBS) symptoms are substantially reduced in office buildings with natural ventilation compared to buildings with air-conditioning. This research concurred with those results and indicated that indoor PM2.5 concentrations improved by 22.8% and PM10 concentrations by 17.9% after retrofitting with openable windows. Nasal congestion ranked as the third most experienced SBS symptom. The post-SBS survey indicated a 25.8% improvement reducing the mean score response for 'blocked or stuffy nose' from a mean score of 3.06 to 2.27.

At first glance the office carbon dioxide concentration appears to have been insignificantly improved by the natural ventilation retrofit. However, the significant research findings are indicated by analysis of the real-time carbon dioxide levels. Prior to the installation and use of openable windows, the office space experienced 12 incidents in which office carbon dioxide levels exceeded 1000 ppm. The office space carbon dioxide level exceeded 1000 ppm for a total of 36 h (8% of total measured office use). During the 5-week post-openable window installation period, the office carbon dioxide level did not once exceed 1000 ppm. The reduction of

>1000 ppm incidents was notable in that the carbon dioxide level was measured at 3-s intervals. The reduction in >1000 ppm carbon dioxide levels reflects in the survey findings with the top two pre-openable window SBS complaints being tiredness and difficulty/poor concentration. The openable windows contributed to 18.3% reduction in tiredness experienced by employees and 20.1% in difficulty/poor concentration. Both these symptoms have a major impact on productivity in offices, so nearly one in five improvements would have massive return on investment as employees make up the majority of business costs.

The review of the literature and the research findings correlate strongly indicating that natural ventilation can significantly improve office environments and employee satisfaction. Natural ventilation is a significant sustainable solution for decreasing the energy usage in buildings, improving thermal comfort and maintaining a healthy indoor environment (Tong et al., 2016).

12.14 Conclusion

This research quantified the impact a natural ventilation retrofit had on improving the indoor air quality of a previously mechanically only ventilated office building. Furthermore, the IAQ findings were correlated with a sick building syndrome survey that was circulated before and after the office building was retrofitted. The relationship between improved indoor air quality and employee well-being is clear with quantified reduction in SBS symptoms experienced by employees. The effectiveness of the natural ventilation solution was also demonstrated with accurate IAQ data indicating significant improvements to IAQ metrics.

A notable observation when analysing the real-time carbon dioxide data, after the openable windows were in use by employees, is that the carbon dioxide levels would reach 850–950 ppm and steadily lower to 650–750 ppm. The data indicates that office users could sense when office carbon dioxide levels where above 800 ppm and instinctively opened the windows. Prior to the openable windows, the carbon dioxide level would continue to rise until after office hours.

The importance of measurement is made clear by this research in that until indoor air quality is measured by organisations the quality of the indoor air breathed by employees is unknown. Furthermore, the possible health implications and medical costs remain unknown. The cost of the retrofit was a once-off capital expenditure of R20 000 with savings immediately in terms of reduced air-conditioning running time. Since the openable windows are controlled by the employees, there is no operational expenditure for the benefits derived from the natural ventilation retrofit, whilst the improvement in tiredness and concentration levels would markedly improve productivity, providing a major return on investment.

In climates such as in Port Elizabeth, South Africa, hybrid ventilation systems provide a true solution to sustainable ventilation within buildings. The sealed office building design with mechanical ventilation is an inappropriate design for warm and temperate climates. Warm and temperate climates can exploit passive design principles for a large portion of the year relying on mechanical ventilation occasionally. In conclusion, natural ventilation should be considered during the design phase of any new construction. However, natural ventilation retrofits can be effective in improving indoor air quality of existing buildings without increasing operational costs over the long term.

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