A new look at smart ventilation for public buildings in the tropics in the post-pandemic era.

Benedict Gumbaketi[1], Stephen Naylor, Lisa Law, Kerry-Anne McBain, Samantha Horseman
James Cook University, Australia
[1]benedict.gumbaketi@myjcu.edu.au,
{stephen.naylor[2], lisa.law[3], kerry.mcbain[4], Samantha.horseman[5]}@jcu.edu.au
0009-0005-3762-2481[1], 0000-0001-7619-6044[2], 0000-0002-9837-6609[3],
0000-0002-3277-2887[4], 0000-0001-5916-311X[5]

Abstract: This paper presents part of a study exploring a quantitative model for linking mechanised ventilation systems to provide acceptable indoor air quality. The lack of an indoor air quality index causes communication discord for occupants, facility managers, and design engineers. Specifically, three statistically correlated indexes to occupants' health symptoms are the indoor discomfort index, indoor air pollutant index, and indoor environmental index. The model will be validated through empirical data to be collected from occupants of three separate institutional buildings at the James Cook University campus and Cairns City in tropical north Queensland in Australia. The next phase of this project entails the integration of applicable computer-based predictive analytical tools to control mechanised ventilation systems.

Keywords: Indoor environmental index, Indoor discomfort index, Indoor Pollution index, IAQ Index

1. Introduction

1.1. Background

A new look at smart ventilation systems implies formulating a unified and quantitative strategy to control mechanised ventilation and air-conditioning (MVAC) systems. In tropical workplace environments, occupants heavily rely on MVAC systems, but face communication discord in controlling indoor air pollution. Despite improved thermal comfort, ensuring acceptable IAQ in this post-pandemic era remains uncertain. By definition, acceptable IAQ is a subjective assessment, with the majority of occupants perceiving the air as breathable and posing no immediate risk (ASHRAE, 2013; ISO, 2016). Considering this subjective IAQ perspective, the urgency spurred by COVID-19 requires objective assessment for rigorous control of ventilation systems to ensure acceptable IAQ. Strategically, a simple metric or index to represent IAQ decay, thereby initiating a demand-based control of the MVAC systems. Currently, the integrated carbon dioxide (CO_2) sensors in the MVAC systems are limited in their functionality, (Morawska et al., 2021), allowing other air pollutants like volatile organic compounds (VOC) and particulate matter (PM) to recirculate undetected within enclosed spaces (Ismail SH et al., 2010). Carslaw et. al., used a detailed chemical model to quantify the impact of 63 VOCs as Secondary Product Creation Potential (SPCP) related to the ventilation rate for dilution (Carslaw & Shaw, 2019). The general Air Quality Health Index (AQHI) based on ambient outdoor air served as a valuable communication tool but is not useful for IAQ assessment (Szyszkowicz, 2019). There is a need to develop correlated MVAC control strategies and techniques based on the perspective of indoor environment, health and well-being of occupants as well as energy efficiency (Cao et al., 2020). The development of low-cost devices to monitor IAQ are useful tools to understand the behaviour of indoor air pollutants (IAP) and potentially impact on the reduction of related health impacts. With the rapidly increasing number of studies, projects, and grey literature based on low-cost sensors in enclosed indoor spaces, they are unable to control the MVAC systems. Chojer et. al. summarises the recent research pertinent to the development of indoor air quality monitoring devices using low-cost sensors (Chojer et al., 2020). This paper presents two empirical quantitative indices directly linked to occupants' health symptoms: the Indoor Air Pollution Index (IAPI) and the Indoor Environmental Quality Index (IEQI). Finally, a data-driven machine learning ventilation control system that supports a demand-control model for IAQ and occupants' health conditions is presented.

In tropical regions such as Cairns in the far north of Queensland, Australia, IAQ issues are very challenging in building design, construction, and facility management. The high humidity and temperatures experienced in the region increase the risk of thermal discomfort, moisture problems, moulds and exposure to contagious bacteria and airborne virus transmission (Hall et al., 2021). The applicable IAQ Standard provides minimum guidelines for design of window opening sizes for natural ventilation to control odour, carbon dioxide (CO_2), thermal comfort and indoor air quality (AS1668.2, 2012). The remarkable Queenslander architecture serves as a noteworthy benchmark for passive ventilation design for the tropics (Naylor, 2016). Conversely, present design emphasis is on positively pressurised enveloping systems to rely on MVAC systems for regulating indoor comfort conditions but with minimum energy requirements (Afroz et al., 2018). Interestingly, energy-efficient office buildings in the tropics only became effective after retrofitting with improved IAQ sensors (Revel et al., 2014).

Recent studies on occupants in tropical public buildings revealed three drawbacks in MVAC system's operation. Firstly, steady-state airflow measured CO_2, but VOCs and other gases were recirculated unnoticed in fractioned-recirculated air (Ismail SH et al., 2010). Secondly, solar radiation entering glass window facades increases thermal radiant field asymmetry and vertical air drafts, potentially creating discomfort for occupants and facilitating air pollutant routes(Azad et al., 2018). Thirdly, there is a lack of cognitive awareness in noticing signs of indoor air pollution concentration and controlling MVAC systems to dilute the air pollutants (Snow et al., 2022). Therefore, a rational approach is to develop a simple numerical scale and index for each of the IAPs and attributed health symptoms. The IAP Index should be simple for all occupants, statutory bodies, the public, and building service engineers to access and communicate. The unified metric or index is an indicator of acceptable indoor air quality (IAQ). Key terms to differentiate for this paper are summarised in Table 1.

Table 1: Descriptions of IAQ evaluation index and references

Description of key IAQ indicator	Reference
An index is constructed from several indicators weighted together to describe the total impact on a certain aspect of the broader environment.	(Sæbø & Alfsen, 1993)
A model incorporates a range of measurable attributes or characteristics as predictor variables of an environmental phenomenon with methodologies to gather seminal data to test the objective that represent the natural system's behaviours.	(Gifford, 2016) (Bennett et al., 2013)
Indoor environmental index (IEI) comprises single or multiple environmental predictor attributes associated with a known air pollutant to cause discomfort and illnesses. IEI is an aggregate of Indoor air pollution index (IAPI) and Indoor discomfort index (IDI).	(Bittel et al., 2018) (Cao et al., 2012)
Indoor air is a summation or aggregate of three indices: the Indoor air pollution index (IAPI), Indoor pollutant standard index (IPSI), Index of air quality (IAQ). The IAPI and IAQ had no association with health symptoms except IAPI. Thus, IAPI measure eight indoor air pollutant. It provides index value range between 0 as lowest pollution level, 10 as highest pollution level and mean as acceptable.	(Cedeño Laurent et al., 2021; Moschandreas & Sofuoglu, 2004; Willers et al., 1996)
Indoor discomfort index (IDI) comprises temperature and relative humidity. An index is a unitless single number ranging from 0 (lower discomfort) to 10 (higher discomfort), of which the mean value is comfortable.	(Ma et al., 2021; Moschandreas et al., 2006)

IAPI measures eight IAPs: carbon dioxide (CO_2), particulate matter (PN2.5, PM10), total volatile organic compound (TVOC), carbon monoxide (CO), formaldehyde (HCHO), bacteria and fungi (measured in Cfu denoting colony forming unit). Acceptable threshold limits for the IAPs are given in Table 2.

Table 2: Indoor air pollution demarcation

Threshold Levels	AQI ppm	$PM_{2.5}$ µg/m^3	PM_{10} µg/m^3	TVOC µg/m^3	CO_2 µg/m^3	HCHO µg/m^3	CO µg/m^3	Fungi Cfu/m^3	Bacteria Cfu/m^3
Maximum	400	150	40	50	1000	60	10	500	500

(Adopted from WHO 2020 Guide to the Indoor Air Quality Standard)(WHO, 2020)

Australian IAQ experts recommend evaluating performance of the ventilation systems to control indoor aerosol transmission (Hyde et al., 2021; Morawska et al., 2021; Morawska & Milton, 2020). In this post-pandemic era, devising strategies to supply acceptable indoor air quality and hygienic indoor environment is the priority for environmental engineers (Azuma et al., 2020). Considering the regulators, OzSAGE is the safe indoor air working group in Australia to provide MVAC system operational guidelines (Crabb et al., 2021) which is summarised in Table 3.

Table 3: Comparing operations of MVAC systems for pre-and post-pandemic era.

IAQ Parameters	Pre-Pandemic IAQ from NCC-2022	Post-Pandemic IAQ From WHO Guide
Relative Humidity	40% to 60%	40% to 60%
Temperature	20^{o} C to 26^{o} C	20^{o} C to 26^{o} C
Airflow Rate	5 to $7L^{-s}$ per person	7 to $10L^{-s}$ per person
Air Change per Hour (ACH)	4 to 6 times	10 to 12times
Air Duct Flushing	Subject to heavy use.	1 time monthly
Filter type	MERV 4 - 12	MERV 14 with ISO ePM1 with HEPA 99.7%
Ventilation windows	25% of floor area	25% of floor area

The common method of improving IAQ is to increase the ventilation rate with well-mixed steady airflow to dilute the generated air pollutants (Zhang, 2020) and lower airborne disease transmission (Aliabadi et al., 2011). This is an optimum approach however is not energy efficient given the tropical conditions. A balance is achievable using a smart predictive IAQ sensors to control indoor air pollutants concentration. Higher relative humidity levels in the tropics propagate airborne pathogens, bacteria, moulds and infectious communicable diseases (Birrell et al., 2023).

1.2. Research Questions

The generic research question is: what have we learned from COVID-19 that will enable us to improve the quality of our workplaces? The crucial lesson learned is that under-ventilated indoor spaces can lead to the infiltration of aerosolised viruses, surpassing the threshold for acceptable indoor air quality. (WHO, 2021). While implementing crucial public health measures such as building closures, isolation, and social density control were imperative risk management process, effectively controlling indoor air quality remains a pressing concern. Plausibly, most pre-pandemic workplace environments were under-ventilated, enabling COVID-19 to spread easily indoors. Therefore, post-pandemic occupancy evaluation using objective-based research methodology should establish a benchmark for comparison.

2. Proposed quantitative indoor air quality evaluation model.

MVAC systems play a major role in providing acceptable indoor air quality and thermal comfort. Indoor air quality directly influences human health and the ability to live and work productively. (Frontczak et al., 2011). Airtight buildings and reduced ventilation rate in the tropics increase indoor air pollution, resulting in building-related illnesses and other health conditions. This study adopts the indoor environmental quality model with nine independent environmental factors: indoor air quality, thermal comfort, lighting, noise, acoustics, spatial comfort, privacy, building-related symptoms, and neurotoxic symptoms. The structural model was tested using the LISREL statistical program with strong internal correlation and association to the dependent variables of environmental satisfaction and productivity. Notable association for indoor air quality, thermal comfort, ventilation had internal correlation of 1.0 and separately to building-related illness was 0.8 (González et al., 1997; Lantrip, 1986; Leifer, 1998). Hence, these four variables highly relate to occupants' symptoms of building- related illness (BRI) form composite factors for the indoor environmental index (IEI).

2.1. The IEI

The IEI comprises of aggregated mean index for IAPI and the IDI, expressly represented as (Sofuoglu & Moschandreas, 2003):

$$IEI = \frac{(IAPI+IDI)}{2} \tag{1}$$

Calculations of the IEI is performed from a tree structure or hierarchically for different indoor air pollutant concentrations and discomfort variables. Figure 1 illustrates the tree structure for computing mean indices.

2.2. The IAPI

IAPI is calculated using eight (8) pollutants associated occupants' health and well-being indoor, namely: CO, CO^2, HCHO, $PM_{2.5}$, PM_{10}, VOC, bacteria, and fungi. A linear function is used to calculate the subindices to derive a mean that is the index for inclusion in the IAPI.

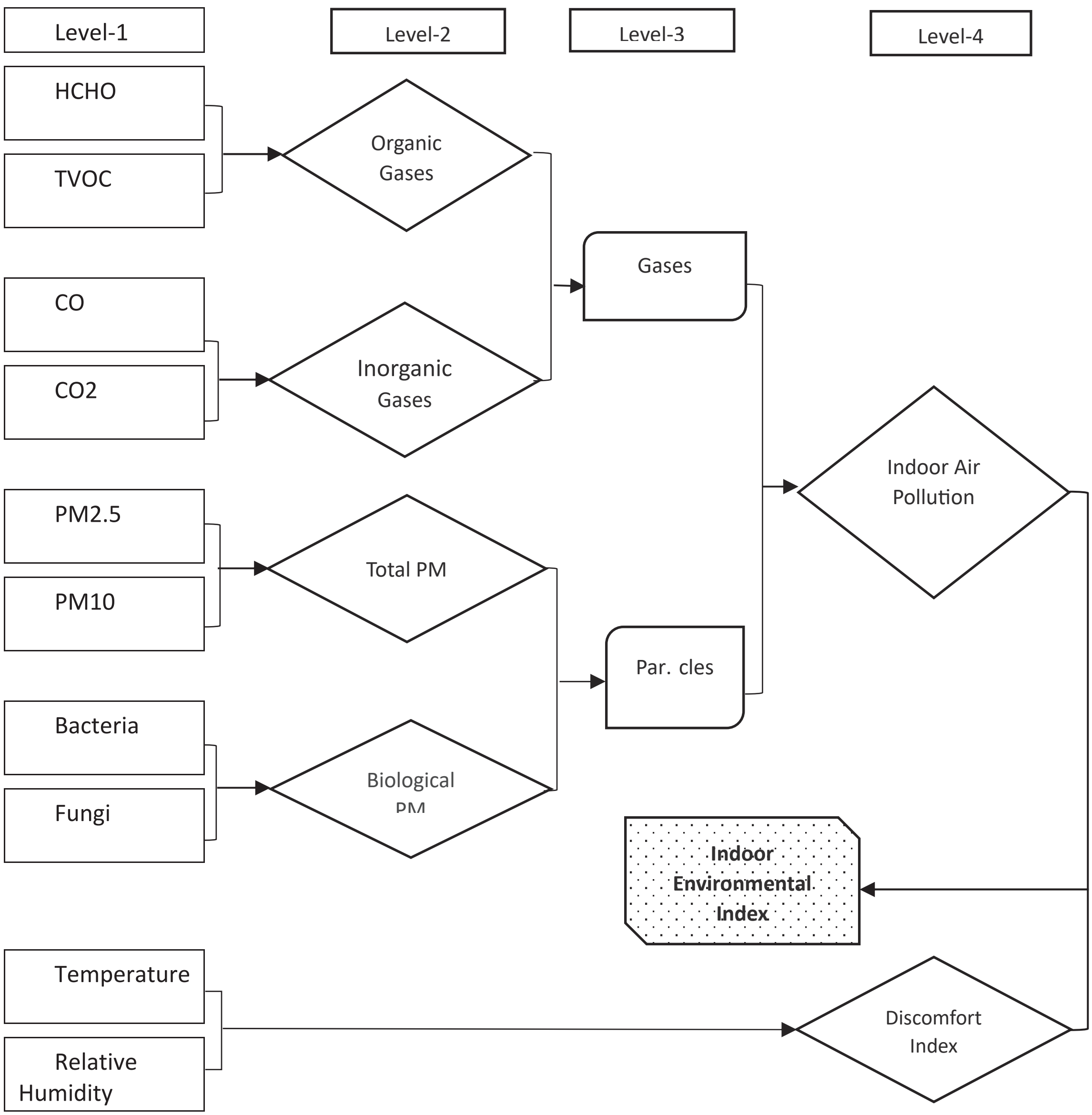

Figure 1: Tree structure for IEI Computation process (Sofuoglu & Moschandreas, 2003)

$$IAPI = \frac{1}{I}\sum_{i=1}^{I} \frac{1}{J} \sum_{J=1}^{J} \frac{1}{K}\sum_{K=1}^{K} 10\left(1 - \frac{C_{ijk}^{max} - C_{ijk}^{obs}}{C_{ijk}^{max} - C_{ijk}^{min}} \left(\frac{C_{ijk}^{dmc} - C_{ijk}^{obs}}{C_{ijk}^{dmc}}\right)\right) \tag{2}$$

for $C^{max} > C^{obs}$ and $C^{dmc} > C^{obs} > C^{min}$

Where *I* is the number of level – 3 groups, I = 2; J is the number of level – 2 groups in each level-3, *J* = 2; *K* is the number of level 1 pollutant variable in each level -2 group, *K* = 2; max is the maximum measured concentration; *min* is the minimum measured concentration; *dme* is the demarcation or threshold concentration; *obs* is the measured concentration in the subject building.

2.3. The IDI

IDI is the aggregated index of two comfort variables: temperature and relative humidity. The standard comfort setting in many MVAC systems is 23°C with 50% relative humidity and considered the mean comfort baseline for average indoor activities (ASHRAE, 2010). A tolerance temperature movement of ± 3°C and 10% RH is the recommended comfortable range. The index is a unitless single number ranging from 0 to 10. A high index value indicates high discomfort, and a low index value indicates low discomfort. Constraints for IDI calculations are: $(i)\ CA_{RH,obs} > 65, (ii)\ CA_{RH,obs} = 25$ when $CA_{RH,obs} < 25, (iii)\ CA_{T,obs} = 28$ when $CA_{T,obs} < 28, (iv)\ CA_{T,obs} = 16$ when $CA_{T,obs} < 16$

$$IDI = \frac{1}{L}\sum_{1=1}^{L} 10 \left(\frac{CA_{i,opt} - CA_{i,obs}}{CA_{i,uci} - CA_{i,lcl}}\right) \tag{3}$$

for $25 > 25^{obs} > 65$ for $RH, and\ 28 > CA^{obs}\ 16$ for T

where *CA* is comfort agent, *L* = 2; *opt* is optimum comfort agent value, T_{opt} = 22°C, RH_{opt} = 45; *tcl* is upper comfort level, T_{uct} = 25°C , RH_{ucl} = 55%; *lcl* is lower comfort level, T_{lcl} = 19°C , RH_{lcl} = 35%; and *obs* is measure comfort agent value in the subject building.

3. Method

3.1. The Database

Computation of the IAPI requires a statistics computer database such as LISREL, SPSS or similar regression analysis tool. The formulation of the index model and the development of the tree structure of the index are performed in the database. Thus, the initial step involves acquisition of skills with simple inferential statistics and the relevant computer-based analytical software.

3.2. Buildings for field study

Data for the operations during peak and off-peak periods will be gathered from the building management systems at the Estate and Facility Management Unit of JCU. This information will form critical historical data on occupants' density, indoor air pollutions, temperature, relative humidity, ventilation rate, air change rate, filter replacements and when major repairs or services were carried out on the subject MVAC systems. The other information is the technical specification of the MVAC related to power outputs, filter types, , thermoset temperature, types of air pollutant sensors, ultraviolet germicide sensors, and other in-built controlling systems on wireless sensors. The previous occupants-satisfaction survey will also provide important additional information. All information will be stored in the University computer database.

There are three methods of data collection:

- Questionnaire survey
- Physical measurement of indoor air pollutants
- Observation and diagnostic review of the MVAC systems.

Three modern academic complexes at James Cook University's Nguma-bada Campus in Cairns and an office building in Cairns City will be evaluated. The selected buildings for this study are airtight and high energy-efficient rated green buildings. The MVAC system uses both active and passive water chill beams for inducing cooler air to various breathable zones and spaces through a duct system. Use of a water chilled beam to cool down surrounding warm air through convection is considered an economical option in the tropics. Considering energy efficiency, the MVAC of each subject buildings is interfaced by a computer-based building management system (BMS) program. Generally, BMS activates scheduled and demand-controlled ventilation in the MVAC to ensure thermal comfort and energy efficiency. The BMS analyses factors like working hours, occupant density, weather conditions, specified group events, and designated breathable air zones to efficiently supply the necessary air volume for thermal comfort indoors.

(i) Ideas Lab D004 (ii) Cairns Institute D003 (iii) GRS Building D011

Figure 2: Selected buildings for field study at Cairns JCU Campus

The Ideas Lab building has a fully glazed facade. In contrast, the Cairns Research Institute complex, representing Ayers Rock, and the GRS Centre have partially glazed facades. The D004 building consists of three floors, featuring tropical plants on outdoor walls and within open atrium spaces. The D003 has two-floor levels with an outer shell made of rusty flat steel sheets, an air gap of 600mm, and an inner-skin layer of tinted glass panels. The third building is identified as D011 uses sandwiched expanded polystyrene wall panels and flat ceiling fixed with air-conditioning diffusers on stilt stumps. All have dynamic indoor spaces that accommodate the activities of university staff, research students and other occupants with a diverse array of academic activities. Typically to all buildings, internal spaces promote co-working environment with opened-floor plan having sufficient lightings and thermally comfortable. The location of indoor environmental services such as ventilation ducts and air vents, and lightings are equally distributed and fixed to or suspended from the ceiling. Because buildings are airtight, acoustically sound and noise proof. These subject buildings are less than ten years old and are energy efficient rated buildings.

3.3. Questionnaire Survey

This questionnaire survey is called Building Occupant-Satisfaction Survey (BOSS), which will be administered online. A total of 30 participants is targeted per buildings as a minimum sampled population. This BOSS project will be conducted two times during the beginning of the year between February and January, then repeated in July/August to target the hot and cooler months respectively. Occupants will participate voluntarily to maintain confidentiality and remain anonymous. The BOSS questionnaire comprises of two parts. Part A gathers demographic data and Part B is the environmental evaluation. Both parts adopt simple multiple choices and rating scale for a more objective-based response. Each response will be assessed using simple inferential statistics and lineal regression analysis to determine internal correlation and coefficients to validate the attributes of the Indoor Environmental Index model(IEI)

3.4. Measurement of air pollution.

Digital loggers will be positioned to measure the eight pollutants for this study. A typical room in one of the subject buildings will be randomly selected for measurements. Each test will be identified by date, building type, location, and timing of the measurements. Digital pollutant loggers will be connected via Wi-Fi network to transmit data direct to the master database computer seamlessly. Environmental comfort data including relative humidity, temperature, wind speed and outdoor weather will be gathered.

3.5. MVAC system observation

Walk-through survey and observations of the respective MVAC systems will provide specific technical information and operational data. This part of the survey will require specific approval from the Estate Division of JCU. Most air handling units and exhaust fans are located on rooftops. Three sets of information are required: (1) the technical specification and operation manuals; (2) the building management systems and the types on controls; and (3) and records of major replacements and maintenance data logbook. This information will explain how the proposed IEI will be integrated.

4. Way-forward

Strategically, the simple IEI is a function of two contributing environmental factors of indoor air pollution and air quality factors. The application of this index is the question at hand. Firstly, we need data from the identified buildings in the tropics. Secondly, a computer database must be identified, for ease of formulating the index for each of the eight pollutants following the proposed hierarchical tree structure. By achieving these two interim challenges will place the project in a position to prototype this project.

5. Conclusion

The development of the Indoor Environmental Index (IEI) will provide a key communication metric. With the aim of controlling and optimising the existing performance of the MVACs, the IEI strategically relates to occupants' health needs for acceptable IAQ. Although many other models and indices exist, their predictive and nonlinear associations are low compared to IAPI, and IDI in this IEI model. With challenges in the tropics to consider, the two factors are closely associated with occupants' health symptoms. The aggregated mean from the eight indoor air pollutants and the two discomfort factors of temperature and relative humidity result in a single number between 0 and 10. This simple indicator communicates to MVAC but also to the occupant, the facility and concerned parties about the quality of indoor air. At this stage, more seminal data are needed to test the model for any empirical application and conclusive assertion of its potential for controlling the MVAC system. More must be done, including integration with the two machine learning algorithms of artificial neural networks using sample field data. Therefore, the way forward is to gather field data and test this mathematical model to derive the indices.

6. Acknowledgement

The authors would like to thank James Cook University for the grant award of $1,215.00 to participate in this conference and toward the research. The Graduate Research School manages the Competitive MRF grant to assist higher degree students, of which I am a beneficiary this year.

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