Environmental Engineering and Management Journal September 2018, Vol.17, No. 9, 2061-2069
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

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HEALTH DAMAGES FROM INDOOR AIR POLLUTION QUANTIFIED USING A NOVEL OFFICE BUILDING DIAGNOSIS METHODOLOGY

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Abstract

This study applied a novel receptor design to the development of an indoor air quality diagnosis (IAQD) system. Indoor air pollutants were converted into simple air quality and health damage indices to evaluate the health risks associated with renovated and unrenovated offices. The outcomes of the IAQD methodology presented R^2 values of 0.705 and 0.700 for renovated and unrenovated offices, respectively. These values indicate moderate level of prediction accuracy. IAQD results related to typical offices showed that the primary contributor to health damage in unrenovated offices was human activity, whereas the primary contributor to health damage in renovated offices was the materials used for decor. Minimizing human activity (sources of major PM_{10} and CO_2) in unrenovated offices could reduce health damage by up to 34.45%. In renovated offices, minimizing the use of toxic materials (sources of HCHO and TVOC) could reduce health damage by up to 56.86%. The proposed indoor air quality diagnosis method can be applied to determine the degree to which pollution sources contribute to indoor air pollution and to provide a simple convenient tool with which to improve indoor air quality and thereby reduce damage to human health.

Key words: damage index, office, indoor air quality diagnosis, receptor, source contribution

Received: April, 2014; Revised final: November, 2014; Accepted: November, 2014; Published in final edited form: September, 2018

1. Introduction

Management programs dealing with indoor air quality (IAQ) are aimed at reducing the severity of pollution in indoor environments for the maintenance of human health. Many people spend more than ten hours a day in the workplace. Equipment such as computers, photocopiers, and printers in office spaces are also sources of air contaminants and construction and remodeling can introduce additional forms of air pollution. Outdoor pollutants, such as vehicle and gas emissions, can also enter indoor environments through ventilation systems (Majumdar et al., 2016; Tham et al., 2004). Exposure to indoor air pollutants can have adverse health effects including fatigue, headaches, nausea, irritation to the upper respiratory system, allergic reactions, and asthma, which are viewed as the symptoms of sick building syndrome (SBS) (Jones, 1999; Kiurski et al., 2016; Sofuoglu, 2008). Several reports have indicated that illness, productivity, and IAQ in office buildings are inter-related (Springston et al., 2002). Moreover, air-conditioned buildings are associated with reduced productivity (Seppanen and Fisk, 2001; Wong and Mui, 2009).

Many air quality index (AQI) systems have been developed to describe ambient air quality, particularly for individuals who are sensitive to pollutants and those suffering from respiratory issues (Bishoi et al., 2009; EPA, 1999). Indexes of outdoor air conditions are often provided in the form of daily reports; however, little research has been conducted on the development of index systems applicable to the indoor environment (Oh et al., 2012; Wang et al., 2008). Identifying hazards associated with indoor air

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can be complicated by the large range of pollutants and variations in human exposure. The chemical mass balance (CMB) receptor model is widely used to quantify the contribution of various pollution sources by conducting component analysis of volatile organic compounds (VOCs) and the concentrations of particulate matter (PM) (Watson and Chow, 2005). The CMB receptor model has recently been used to estimate the contribution of various air pollution sources and the resulting human exposure (Gokhale et al., 2008; Jeon et al., 2005). This study combines IAQ measurements with assessments related to health damage in the form of an indoor air quality diagnosis (IAQD) system. The IAQD system identifies indoor air pollutants in order to increase the effectiveness of measures aimed at reducing the negative effects of pollutants on human health.

2. Materials and methods

2.1. Building description and office selection

An eight-story office building located in an industrial center in Taipei, Taiwan was the subject of this study. The building was constructed in 2006 and has an area of 5,320.12 m^2. Office floors are largely open but receive only a minimum of fresh air. They are serviced by a central air conditioning system with fan coil unit (FCU). Work stations are separated using partitions and each occupant was allocated a desktop computer or laptop. A central air conditioning system air handing unit (AHU) was also used on the fourth floor. Fresh air was brought in from outside the building for 15 min every hour.

IAQ standards of the Taiwan Environmental Protection Agency (Taiwan EPA) address nine indoor air pollutants: coarse particles (PM_{10}), fine particles ($PM_{2.5}$), ozone (O_3), carbon monoxide (CO), carbon dioxide (CO_2), formaldehyde (HCHO), total volatile organic compounds (TVOC), bacteria, and fungi. Nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) are also typically considered air pollutants due to their effects on human health (Jones, 1999). Air quality sampling was conducted on the second, third, fourth, and sixth floors of the office building. The number of individuals and the activities they conducted remained the same throughout the study period. Indoor and ambient air sampling was performed during the workdays of May 13 and 20, 2010. The study involved continuous monitoring for each sampling point throughout office hours. The number of sampling points was determined in accordance with the guidelines of the Hong Kong Productivity Council for Environmental Protection Department (HK EPD, 2003). The four floors covered a total area of 2,975.87 m^2, which required a minimum of six sample points to cover all four floors.

2.2. Indoor air quality sampling

An AEROCET-531 portable instrument with laser diode (Met One Instruments, Inc., USA) was used to measure PM_{10} and $PM_{2.5}$ concentrations. A portable KD AirBoxx (KD Engineering, Inc., USA) was used to monitor gaseous air pollutants (CO_2, CO, and SO_2). This instrument is equipped with referenced non-dispersive infrared and electrochemical sensors with resolutions of 1 and 0.1 ppm, respectively. A portable IAQ RAE PGM5210 measurement device (RAE Systems Inc., USA) was used to monitor TVOC and NO_2. This device includes a 10.6 eV photoionization lamp and electrochemical sensors with resolutions of 0.01 and 0.1 ppm, respectively. A formaldehyde htV instrument (PPM Technology, Caernarfon, UK) with electrochemical sensors (resolution of 0.01 ppm) was used to monitor HCHO. O_3 concentrations were measured by using an ozone monitor (model 2B Technologies, Inc.) with a UV absorption of 254 nm and resolution of 0.1 ppb. For quality assurance and control, all instruments were calibrated with air and standard span gas prior to use. PM concentrations were measured using an AEROCET-531 (Met One Instruments, Inc., USA) handheld particle counter and compared with those reported by the Sanchong air quality monitoring (AQM) station of new Taipei city of Taiwan. The correlation coefficients between the Sanchong AQM and the AEROCET-531 data were 0.895 (n = 10) and 0.706 (n = 11) for PM_{10} and $PM_{2.5}$ particles, respectively. These coefficients were used as references with which to adjust the results of the AEROCET-531 sampler. The Anderson portable air sampler has a d_{50} collection efficiency of 8~24 µm and 1~8µm for stage 0 and stage 1, respectively. Two duplicate samples of bacteria and fungi were measured. The concentration of bioaerosol was calculated using Eq. (1):

$$\text{Bioaerosol (CFU m}^{-3}\text{)} = \tag{1}$$

$$= \frac{(\text{Count of stage 0} + \text{Count of stage 1})}{\text{Flow rate} \times \text{sampling time}} \times 1000$$

2.3. Indoor air quality index

This study established the following IAQI values: 0, 50, 100, 150, 200, 300, and 500, in which an index value of 150 corresponds to IAQ standards in Taiwan. The values of 50, 100, 200, 300, and 500 correspond to reference indices provided by the AQI of United States Environmental Protection Agency (US EPA), the pollutants standards index (PSI) of Taiwan, World Health Organization (WHO) reports, and the United States National Institute for Occupational Safety and Health (NIOSH). These values are the defined limits for time-weighted average (TWA), short-term exposure limit (STEL), and immediately dangerous to life and health (IDLH) concentrations.

However, the relationship between bioaerosol concentration and health response remain undefined. Thus, this study created a bioaerosol air pollution index by extrapolating for the IAQI. Eleven indoor air pollutants, namely, PM_{10}, $PM_{2.5}$, SO_2, NO_2, O_3, CO,

CO_2, HCHO, TVOC, bacteria, and fungi, are presented in the IAQI (Table 1). As the IAQI value increases, IAQ becomes worse. The IAQI value was calculated by using Eq. (2).

$$\mathrm{IAQI}_i = \frac{(P_{up} - P_{low})}{(C_{up} - C_{low})} \times (C_i - C_{low}) + P_{low} \tag{2}$$

where C is the concentration of indoor air pollutants i, C_{up} and C_{low} are the upper and lower thresholds of the concentration for air pollutant i, P_{up} and P_{low} are the IAQI values corresponding to C_{up} and C_{low}.

2.4. Health damage index assessment

IAQI values for each air pollutant were divided using the IAQI benchmark value of 150 (corresponding to IAQ standard of Taiwan) to obtain a damage ratio (DR) value for each air pollutant. The sum of DR values for the 11 air pollutants was used to calculate the total damage index (DI). A DI value greater than 1.0 indicates a potential health concern, according to Eq. (3).

$$\text{Damage index (DI)} = \sum_{i=1}^{n} DR_i = \sum_{i=1}^{n} \frac{IAQI_i}{IAQI_{IAQS}} = \sum_{i=1}^{n} \frac{IAQI_i}{150} \tag{3}$$

where DR is the damage ratio of IAQIi and $\mathrm{IAQI}_{\mathrm{IAQS}}$, $IAQI_i$ is the IAQI value of indoor air pollutant i, and $IAQI_{IAQS}$ is the benchmark value of IAQI corresponding to the IAQ standard.

2.5. Indoor air quality diagnosis: methodology

Sources of air pollution in the office space were categorized into four types: outdoor air pollution, equipment, remodeling materials, and human loading. The contribution of outdoor air pollution to indoor office spaces was calculated using the percentage of fresh air and the removal efficiency of air filtration systems. To calculate the effects of office equipment, we combined two emission sources (laser printers and photocopiers) in the category of photocopying equipment. A database of emission values from building materials used in remodeling was obtained from the Architecture and Building Research Institute of Taiwan. We also employed local test or research data from previous studies on air pollution sources (Black, 1999; Lin, 2004; Chiang and Lee, 2004; Chiang and Shao, 2008; Hung, 2002; Lee et al., 2001; Scheff et al., 2000) (Table 2). Air pollution sources and emission rates must be recorded and created in this study for the IAQD methodology necessary.

A database on the emissions encountered in office environments was used to obtain emission coefficients for various pollution sources (see Table 2). Previous studies have indicated the contribution of pollution source j contributes to the overall concentration of pollutant i at a given site can be calculated by multiplying the emission rate of pollution source j by the intensity of the activity at pollution source j and then divide the results by the volumetric flow rate of fresh air (m^3 h^{-1}) from outside. For example, the emission rate (ER) of ozone from photocopying equipment is X mg/copy, operating at intensity (S) of Y copy/hr at an indoor ventilation rate (m^3/ hr) of Q. Thus, the concentration of indoor air pollution from each source can be estimated using Eq. (4).

$$C_{ij} = \frac{ER_{ij} \times S}{Q} \tag{4}$$

where C_{ij} is the concentration of air pollutant i from pollution source j at a given site (mg m^{-3}), ER_{ij} is the emission rate of air pollutant i from source j (units are listed at Table 2), S is the intensity of activities at a given site (see Table 3), and Q is the volumetric flow rate of fresh air (m^3 h^{-1}) from outside (see Table 3).

The solution procedure used in the IAQD is based on the concept of receptors. The proposed IAQD methodology determines the contribution of various pollution sources to the total IAQ. Linear programming was used to achieve optimal solutions. The data were recounted using data dynamic exchange and new data were returned to the linear programming module via a trial and error process aimed at optimizing the results. Thus, Eq. (5) provides DI for air pollutant i.

Table 1. Indoor air quality index

IAQI value	*Gaseous air pollutant*							*Particle*		*Bioaerosol*	
	HCHO	***TVOC***	***CO***	***CO_2***	***O_3***	***SO_2***	***NO_2***	***CP[a]***	***FP[b]***	***B[c]***	***F[d]***
Unit	ppm							μg m^{-3}		CFU m^{-3}	
0	0	0	0	≤ 400	0	0	0	0	0	0	0
50	0.01	0.09	2.0	600	0.03	0.035	0.053	15	12	500	250
100	0.03	0.13	4.0	800	0.05	0.075	0.100	50	25	1000	500
150	0.08	0.56	9.0	1000	0.06	0.185	0.360	75	35	1500	1000
200	0.75	4.6	15.4	5000	0.12	0.304	0.649	350	135	2000	1500
300	2	21.4	30.4	30000	0.37	0.604	1.249	420	250	4000	3500
500	20	38.0	50.4	40000	0.60	1.004	2.049	600	500	10000	9000

[a]CP: coarse particle (PM_{10}); [b]FP: fine particle ($PM_{2.5}$); [c]B: bacteria; [d]F: fungi

Table 2. Database of emissions encountered in office environments

Sources of air pollution		***Unit***	***Gaseous air pollutants***				***Particles***		***Bioaerosols***	
			TVOC	***HCHO***	***O_3***	***CO_2***	***CP***	***FP***	***B***	***F***
Equipment operation	Laser printer	μg copy^{-1}	5.7	N.A.	1.2	N.A.	N.A.	N.A.	N.A.	N.A.
	Photocopier	ng copy^{-1}	3253[a]	659.92	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
	Personal computer	mg h^{-1}	12.2	N.A.	<0.02	N.A.	0.05	N.A.	N.A.	N.A.
Remodeling materials	Plywood	μg m^{-2} h^{-1}	98.81	686.15	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
	PVC floor	μg m^{-2} h^{-1}	28.90	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
	Cubicle wall	μg m^{-2} h^{-1}	360.67	29.41	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Human loading	Activity	mg h^{-1} per person	N.A.	N.A.	N.A.	43,102	N.A.	N.A.	N.A.	N.A.
		mg h^{-1} per person	N.A.	N.A.	N.A.	N.A.	1.28	0.154	N.A.	N.A.
		CFU h^{-1} per person	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	13,620	10,020

[a]TVOC as total of benzene, toluene, and styrene; [b]N.A. as not available

Table 3. Characteristics of renovated and un-renovated offices

Type of office				***Un-renovated office***	***Renovated office***
Building age				***5 years***	***4.6 months***
Space volume (L × W× H)				47.5 × 15 × 2.46	20.5 × 17.6 × 2.46
Outdoor air pollution	Air infiltration	Flow rate (Q, m^3 h^{-1})		1314.56	576.92
		CO_2 concentration of supply air (C_S, ppm)		1,250	758
		CO_2 concentration of return air (C_R, ppm)		1,305	805
		CO_2 concentration of outside air (C_O, ppm)		379	379
		Outdoor air (%)[a]		5.94	11.03
Intensity of activities	Human loading	Employees		64	14
		Activity		Document processing	
	Equipment operation	Personal computers		113	30
		Printing equipment	Photocopier	1 (20 copy hr^{-1})	1 (few copy hr^{-1})
			Laser printer	43 (1.5 copy hr^{-1})	0
	Remodeling materials	Plywood (m^2)		955.02	378.68
		PVC floor (m^2)		667.5	360.8
		Cubicle wall (m^2)		1069.16	304.47

[a]Percentage of outdoor air, determined as follows: $(C_R-C_S) / (C_R-C_O) \times 100\%$

$$DI_i = \sum_{j=1}^{p} DR_{ij} m_j \tag{5}$$

where DR_{ij} is the damage ratio of air pollutant i emitted from source j, and m_j is the calculated contribution of source j to total health damage.

The investigation into the contribution of specific sources of indoor air pollution was conducted on two floors in the office building, the characteristics of which are presented in Table 3.

The fourth floor is an unrenovated office space with office equipment and a higher density of workers than the other five offices. Most of the occupants on these two floors perform document processing tasks; therefore, printers and photocopiers are distributed throughout the workspace. Paint was used on the wall surfaces and adhesives were used on the PVC floors. Plywood paneling was used as wall decor.

A value of 9 was adopted as the minimum efficiency reporting value (MERV) and assigned removal efficiencies of 85% and 50% for coarse (PM_{10}) and fine ($PM_{2.5}$) particulate matter, respectively (Burroughs and Hansen, 2008). To validate the accuracy of the IAQD methodology, we determined the values of r and *R-squared* (R^2), a method widely used for the validation of models.

3. Results and discussion

3.1. Indoor air quality analysis of six offices

Descriptive results related to air pollutants, including the minima, maxima, mean, and standard deviation, were obtained from the second, third, fourth, and sixth floors of the office building (Table 4). Our results indicated low indoor concentrations of NO_2, SO_2, and O_3. Low SO_2 concentration may be due to an absence of activities that involve the burning of sulfur-containing materials in office spaces. The presence of ozone is likely due to operation of photocopying equipment, which was a low-frequency activity in these offices. CO concentrations were high in offices D and E where the AHU ventilation system was used. CO concentrations were lower in offices A, B, C, and F where the FCU system was used.

CO_2 is not considered an indoor air pollutant; however, it is a critical indicator of air ventilation of indoor. Hige average concentrations of CO_2 were detected in offices B, D, E, and F. An AHU ventilation system that draws fresh air from outside was installed in offices D and E; however, the CO_2 concentrations in these spaces were not significantly less than those in FCU ventilated offices. Due to the large number of employees in offices D and E, the volumetric flow rate of fresh air from outside was insufficient to meet the needs of these high-density spaces.

Low TVOC concentrations were measured in all offices except for office D, which was significantly greater than that of the other five offices. The highest concentration of HCHO was obtained in office A, followed by office E.

In all offices, the average PM_{10} and $PM_{2.5}$ concentrations were low: PM_{10} (25.8-57.5 μg m^{-3}) and $PM_{2.5}$ (8.3-50.5 μg m^{-3}). Office E (AHU ventilation) had the lowest PM_{10} concentration. FCU ventilated offices (A, B, and C) presented higher concentrations of particulate matter than did the AHU ventilated offices. This demonstrates that the air filtration provided by an air-conditioning system can reduce the concentration of large-diameter particles from outdoor as well as recirculated indoor air.

High concentrations of airborne bacteria were present in office E. This space had the fewest employees but high humidity due to the adjacent pantry and water damage, which may account for the high concentrations of bacteria. The average fungi concentration for the six offices ranged from 29 to 424 CFU m^{-3}. Fungi concentrations in office A were high because it contains a large number of plants.

3.2. Application of IAQD methodology

Two office floors were selected for an investigation into the factors contributing to indoor air pollution. The second floor housed an office space that had been renovated 4.6 months previously. The fourth floor was an unrenovated office space with the largest density of office equipment and workers among all of the offices in this study. IAQ analysis was conducted on the renovated offices on the second floor and unrenovated offices on the fourth floor. Table 5 presents the average air pollution levels inside the two offices and outside the building.

NO_2, SO_2, and O_3 concentrations in renovated offices were lower than those in unrenovated offices or were not detected. Ratios of indoor to outdoor concentrations (I/O) of NO_2, SO_2, and O_3 were all below measurement thresholds for the renovated office. The unrenovated office had an O_3 I/O ratio of 0.3, whereas the NO_2 and SO_2 ratios could not be determined because the concentrations of these analytes were very low in the indoor environment. This office building had very low air throughflow, which prevented outside pollutants from easily entering the building (Horacio and Lawrence, 2007).

Table 4. Estimation of indoor air quality (Avg.± S.D.) in six offices

Case	*Office A (n=4)*	*Office B (n=2)*	*Office C (n=2)*	*Office D (n=6)*	*Office E (n=4)*	*Office F (n=5)*
NO_2 (ppm)	N.D.	N.A.	N.A.	N.D.	N.A.	N.A.
SO_2(ppm)	N.D.	N.A.	N.A.	N.D.	N.A.	N.A.
TVOC(ppm)	0.39 ± 0.03	0.46 ± 0.17	0.24	1.07 ± 0.09	0.30 ± 0.03	0.26 ± 0.05
O_3 (ppm)	N.D.	0.01	N.D.	0.01	N.D.	N.D.
CO_2(ppm)	827 ± 71	1,171 ± 3	867 ± 16	1,343 ± 11	1,155 ± 95	1,404 ± 115
CO(ppm)	0.23 ± 0.21	2.75 ± 0.07	2.60 ± 0.14	3.27 ± 0.48	3.20 ± 0.27	2.42 ± 0.15
HCHO(ppm)	0.18 ± 0.02	0.07 ± 0.03	0.03 ± 0.01	0.09 ± 0.05	0.11 ± 0.03	0.06 ± 0.02
CP (μg m^{-3})	32.0 ± 17.4	40.5 ± 7.8	57.5 ± 7.8	31.0 ± 11.7	25.8 ± 5.5	28.6 ± 10.2
FP (μg m^{-3})	12.0 ± 0.8	34.0 ± 7.1	50.5 ± 6.4	8.3 ± 1.6	21.3 ± 5.1	25.4 ± 8.1
B (CFU m^{-3})	428 ± 54	850 ± 117	621 ± 18	770 ± 30	877 ± 295	314 ± 78
F (CFU m^{-3})	424 ± 59	158 ± 177	71 ± 6	325 ± 40	50 ± 15	29 ± 9

[a]*N.D. denotes not detected.*

Table 5. Indoor air pollution concentrations (Avg. ± S.D.)[a] in renovated and un-renovated offices

IAQ item	*Renovated office*	*Un-renovated office*	*Outdoor air*	*I/O-Re*[b]	*I/O-Un-re*[c]
TVOC (ppm)	0.39 ± 0.03	1.07 ± 0.09	N.D.	N.A.	N.A.
NO_2 (ppm)	N.D.	N.D.	0.01	N.A.	N.A.
O_3 (ppm)	N.D.	0.01	0.03	N.A.	0.3
SO_2 (ppm)	N.D.	N.D.	0.01	N.A.	N.A.
CO_2 (ppm)	827 ± 71	1,343 ± 11	379	2.2	3.5
CO (ppm)	0.23 ± 0.21	3.27 ± 0.48	2.9	0.1	1.1
HCHO (ppm)	0.18 ± 0.02	0.09 ± 0.05	0.11	1.6	0.8
CP (μg m^{-3})	32 ± 17.4	31 ± 11.7	66	0.5	0.5
FP (μg m^{-3})	12 ± 0.8	8.3 ± 1.6	25	0.5	0.3
B (CFU m^{-3})	428 ± 54	770 ± 30	307	1.4	2.5
F (CFU m^{-3})	424 ± 59	325 ± 40	933	0.5	0.3

[a]*Concentration of indoor air pollutants (average and standard deviation);*
[b]*I/O-Re: Ratio of average concentration inside renovated office to average outdoor concentration;*
[c]*I/O-Un-re: Ratio of average concentration inside un-renovated office to average outdoor concentration.*

Nonetheless, the average CO concentration on the unrenovated floor (3.27 ppm) was higher than in the renovated floor (0.23 ppm). The air intake from outside was close to a parking area for motorcycles and trucks as well as a designated smoking area, which may have allowed CO to enter through the heating, ventilation, and air conditioning (HVAC) systems. Indoor TVOC and HCHO concentrations were consistently greater than the concentrations measured in outside air (OA). The unrenovated office had an average TVOC concentration of 1.07 ppm, which was higher than that of the renovated office (0.39 ppm). VOCs in indoor air may be original or secondary air pollution. Low molecular volume VOCs can be re-emitted into the air at a high velocity (Guo, 2011; Zuraimi et al., 2004). The average HCHO concentration in the renovated and unrenovated offices was 0.18 and 0.09 ppm, respectively. The ratio of indoor to outdoor HCHO concentrations was 1.6 for the renovated offices and 0.8 for the unrenovated offices.

The I/O ratios for PM_{10} particulates matter were 0.5 in the renovated as well unrenovated offices. The I/O ratios for $PM_{2.5}$ particulates matter were 0.5 for the renovated and 0.3 for the unrenovated offices. These analytical results indicate that the original source was OA pollution. Particulate matter from outdoor sources may enter the indoor environment through the air conditioning system. Filtration is an efficient means of removing PM particles (Wong et al., 2006). The average concentration of CO_2 in the unrenovated office was approximately 0.6 times greater than that observed in the renovated office. The average concentration bacterial matter was 770 CFU m^{-3} in the unrenovated office, which exceeded the 428 CFU m^{-3} in the renovated office. The higher CO_2 and bacterial concentrations can be attributed to the high density of workers in the unrenovated office, which was approximately four times that in the renovated office. The concentration of fungi in the renovated office was greater than that in the unrenovated office; however, significantly higher fungi concentrations were measured outside the renovated office.

3.2.1. Identification of air pollution sources and estimation of IAQ

The percentages of fresh outdoor air in the unrenovated and renovated offices were 5.94% and 11.03%, respectively. We used the number of occupants to calculate human inhalation (human loading) with CO_2 concentrations calculated according to the rate of metabolism. The occupancy of the unrenovated office space (64 people) was greater than that of the renovated office (14 people). Typical office activities, such as document processing, were performed in both offices; therefore, we included photocopying equipment, personal computers, and laser printers in the model. Remodeling materials included plywood, PVC flooring, and cubicle walls. Despite the fact that emission concentrations decrease over time, zero emissions can never be reached (Brown, 2002). Thus, concentrations of 0.01% HCHO and TVOC would remain in the unrenovated office even after five years..

3.2.2. Health damage assessment

The highest health damage values in unrenovated offices were for human activity (3.02) followed by personel computers (1.00). The highest health damage values in renovated offices were plywood (1.82) followed by human activity (1.25 (Fig. 1). The primary air pollutants contributing to health damage were CO_2 (33.44%) in unrenovated offices and HCHO (61.54%) in renovated offices.

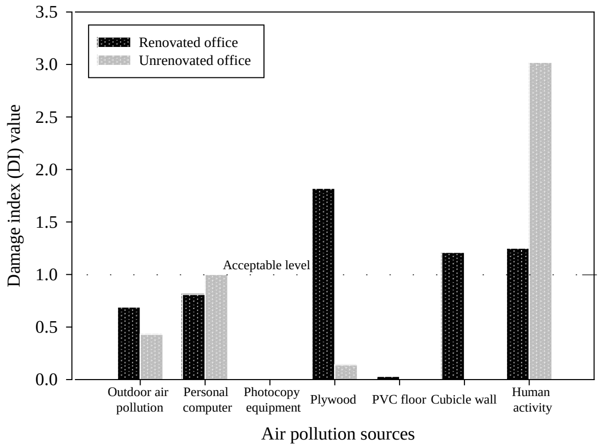

Fig. 1. Index of health damage due to indoor air pollution sources in un-renovated and renovated offices

In renovated as well as unrenovated offices, the air pollutants from outdoor sources that posed the greatest risk to health were SO_2, NO_2, O_3, and CO.

In renovated offices, personal computers were the primary source of TVOC, followed by plywood and cubicle walls. In unrenovated offices, personal computers were the primary source of TVOC. In the renovated offices, plywood and cubicle walls were the main sources of formaldehyde. In the unrenovated offices, OA pollution was the primary source of formaldehyde followed by plywood.

In both renovated and unrenovated offices, PM_{10} was the main air pollutant posing a risk to human health and most of the PM_{10} was due to human activity. In renovated offices, human activity was the major source of $PM_{2.5}$, followed by OA pollution. In unrenovated offices, human activity was the major source of $PM_{2.5}$.

In both renovated and unrenovated offices, bacteria posed the greatest risk to human health and most of the bacteria were due to human activity. In renovated offices, human activity was the main source of fungi, followed by OA pollution. In unrenovated offices, human activity was the major source of fungi.

In renovated and unrenovated offices, the air pollutants that posed the greatest risk to health were PM_{10}, $PM_{2.5}$, CO_2, bacteria, and fungi, most of which can be attributed to human activity. Pollution levels are strongly correlated with sources of air pollution and building characteristics (He et al., 2004; Kopperud et al., 2004). Even though the DI values for OA pollution and personal computers were low, it must be remembered that the chemicals responsible for increasing the incidence of SBS symptoms or irritation often occur in low concentrations (Springston et al., 2002).

3.3. Outcome of the IAQD methodology

Figs. 2 (A) and (B) show the source distribution and prediction accuracy in the unrenovated office, where human activity accounted for 34.45% of the damage to human health followed by personal computers (29.02%). The outcome parameters were *r* (0.836) and *R squared* (0.700).

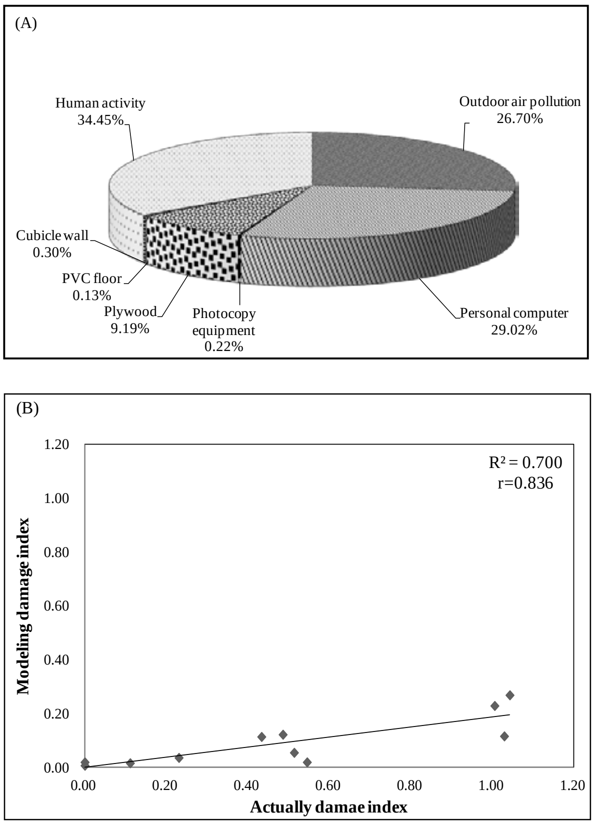

Fig. 2. Results for unrenovated offices: (A) Contribution of various pollutant sources; (B) accuracy of model prediction results against actual damage indices

Human activity accounts for 33.44% of the CO_2 and 25.83% of PM_{10} in the unrenovated office, which represents 59.27% of the total pollution. Polluted air often remains undiluted in the indoor environment, such that the concentrations of CO_2 and other pollutants continue to grow. IAQ values generally present an increase when ventilation conditions are poor (Gadkari and Pervez, 2007; Kim et al., 2001).

Figs. 3 (A) and (B) present the source distribution and prediction accuracy in the renovated office, in which the main pollutant contributing to health damage was decor materials (including cubicle walls, plywood, and PVC flooring), which accounted for 56.86% of the total. The outcome parameters were *r* (0.840) and *R squared* (0.705).

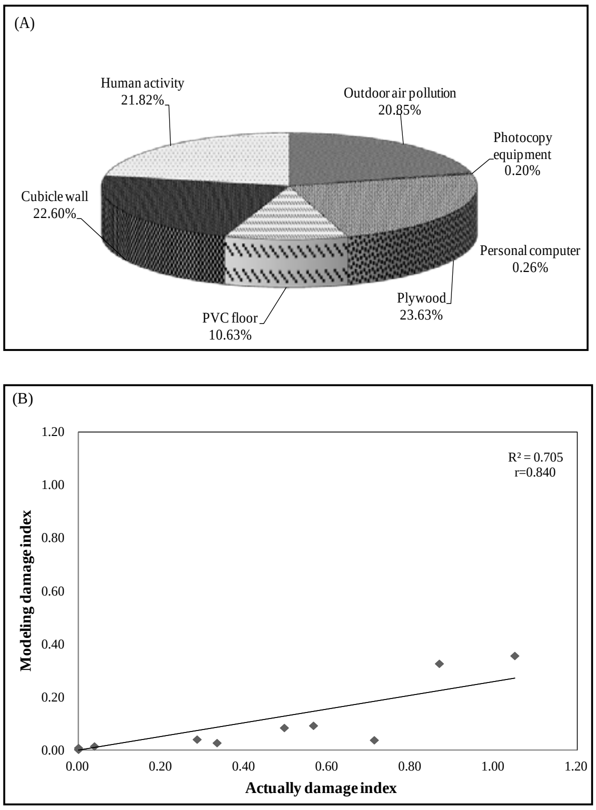

Fig. 3. Results for renovated offices: (A) Contribution of various pollutant sources; (B) accuracy of model prediction results against actual damage indices

In renovated offices, the main source of air pollution was plywood (23.63%), which contributed to 61.54% of the HCHO, and the cubicle walls (22.60%), which contributed to 56.20% of the TVOC. As in the study by Brown (2002), the materials used in the decor of renovated offices in this study also emitted TVOC.

These results clearly indicate the health hazards presented by air pollutants in renovated and unrenovated offices. In unrenovated offices, the primary source of unhealthy pollutants was human activity, followed by personal computers. In renovated offices, the primary source of unhealthy pollutants was the materials used in the decor.

The number of employees in the unrenovated office (64 people) was 4.5 times greater than that in the renovated office (14 people). This led to the release of pollutants, such as particles released through human metabolism or carried indoors through adhesion to clothing. The poor IAQ observed in the unrenovated office can be attributed to insufficient HVAC maintenance and inadequate air ventilation, despite the fact that twice as much fresh air was being supplied to the unrenovated office as the renovated office (Hummelgaard et al., 2007). The high PM_{10} and CO_2 concentrations observed in this study are likely due to the high concentration of workers and poor ventilation (Reynolds et al., 2001). Personal computers represent the second most important health hazard. According to Destaillasts et al. (2008), the emission of air pollutants from printers and copiers generally exceeds those from computers; however, in this study, the use of photocopying equipment was relatively low in both renovated and unrenovated offices.

Materials used in the decor represent the primary health hazard in the offices renovated less than six months previously. According to Brown (2002), over 90 % of the concentration of VOCs volatilizes in the 20 to 35 weeks (approximately five to nine months) following renovations . Furthermore, the fresh air flow of 576.92 m^3hr^{-1} in the renovated office is approximately one half that in the unrenovated office (1314.56 m^3hr^{-1}). Under these poor ventilation conditions, its takes much longer for VOCs to release from decor materials.

The proposed IAQD methodology resulted in R^2 values of 0.705 for renovated and 0.700 for unrenovated renovated offices, which indicate moderate to high prediction accuracy. The proposed methodology proved more accurate for renovated offices (R^2: 0.705) than for unrenovated offices (R^2: 0.700). This difference can be attributed to considerable contribution to pollution levels from newly installed building materials. Nonetheless, the intensity of activities performed in the unrenovated office exceeded that in the renovated space and the air-conditioning system provided ventilation and air filtering.

The prediction results from the IAQD for unrenovated and renovated offices (Fig. 2(B) and Fig. 3(B)) appear to have been underestimated, perhaps due to a failure to consider (1) pollution sources such as cleaning products, consumer products, or aromatic agents, (2) the fact that actual emission factors may be greater than the values in the databases; (3) re-emission of PM and desorption of VOCs (Wolkoff, 1999; Zuraimi et al., 2004); and (4) the settlement and re-entrainment of suspended particles. However, an acceptable R-*squared* value suggests that underestimation of damage index values would not affect the contribution to health damage.

4. Conclusions

This study developed an IAQD methodology based on the concept of receptors. The proposed method can be applied to determine the degree to which pollution sources contribute to indoor air pollution and to provide a simple convenient tool with which to improve indoor air quality and thereby reduce damage to human health.

The outcomes of the IAQD methodology presented R^2 values of 0.705 and 0.700 for renovated and unrenovated offices, respectively, which indicate moderate prediction accuracy.

IAQD results indicate that in typical unrenovated offices, human activity is the primary factor contributing to health damage, whereas the materials used in decor are the greatest threat in renovated spaces. Minimizing human activity (the major source of PM_{10} and CO_2) by increasing ventilation in unrenovated offices could decrease health damage by up to 34.45%. In renovated offices, minimizing decor materials (HCHO and TVOC sources) by replacing these harmful materials with healthier materials could reduce health damage by up to 56.86%.

Future studies could include other parameters and more extensive databases, such as consumer pollution sources or the dispersion concentrations of various materials, in order to increase the accuracy of the prediction model.

References

Bishoi B., Prakash A., Jain V.K., (2009), A Comparative study of air quality index based on factor analysis and US-EPA methods for an urban environment, *Aerosol and Air Quality Research*, **9**, 1-17.

Black M.S., Worthan A.G., (1999), *Emissions from Office Equipment*, The 8th Int. Conf. on Indoor Air Quality and Climate, Indoor Air 99, vol. 5, Edinburgh, Scotland, 1-7.

Burroughs H.E., Hansen S.J., (2008), *Building Security and Safety: Readying Your Building for Extraordinary Environmental Stress*, In: *Managing Indoor Air Quality 5th Ed*, Fairmont Press, United States of America, 233-234.

Brown S.K., (2002), Volatile organic pollutants in new and established buildings in Melbourne, Australia, *Indoor air*, **12**, 55-63.

Chiang C.M., Lee C.C., (2004), *A Study to Establish Databank of VOCs on Adhesives Materials*, Architecture and Building Reaserch Institute, Ministry of the Interior, Republic of China, Taiwan.

Chiang C.M., Shao W.C., (2008), *The Appraisal Procedures of Healthy Furniture Labeling and the Standard Test Methods of the Furniture*, Ministry of the Interior, Republic of China, Taiwan.

Destaillats H., Maddalena R.L., Singer B.C., Hodgson A.T., McKone T.E., (2008), Indoor pollutants emitted by office equipment: A review of reported data and information needs, *Atmospheric Environment*, **42**, 1371-1388.

Gadkari N.M., Pervez S., (2007), Source investigation of personal particulates in relation to identify major routes of exposure among urban residentials, *Atmospheric Environment*, **41**, 7951-7963.

EPA, (1999), *Air Quality Index Reporting*, 40 CFR Part 58, Vol. 64, No. 149, U.S. Environmental Protection Agency, On line at: http://www.epa.gov/ttn/oarpg/t1/fr_notices/airqual.pdf

Gokhale S., Kohajda T., Schlink U., (2008), Source apportionment of human personal exposure to volatile organic compounds in homes, offices and outdoors by chemical mass balance and genetic algorithm receptor models, *Science of the Total Environment*, **407**, 122-138.

Guo H., (2011), Source apportionment of volatile organic compounds in Hong Kong homes, *Building and Environment*, **46**, 2280-2286.

He C., Morawska L., Hitchins J., Gilbert D., (2004), Contribution from indoor sources to particle number and mass concentrations in residential houses, *Atmospheric Environment*, **38**, 3405-3415.

HK EPD, (2003), *A Guide on Indoor Air Quality Certification Scheme for Offices and Public Places*,

Hong Kong Productivity Council for Environmental Protection Department, 5-6.
Horacio T.A., Lawrence W., (2007), Personal exposures to volatile organic compounds among outdoor and indoor workers in two Mexican cities, *Science of the Total Environment*, **376**, 60-71.
Hummelgaard J., Juhl P., Sæbjörnsson K.O., Clausen G., Toftum J., Langkilde G., (2007), Indoor air quality and occupant satisfaction in five mechanically and four naturally ventilated open-plan office buildings, *Building and Environment*, **42**, 4051-4058.
Hung C.H., (2002), *The Characteristic and Damage Assessment of Indoor Volatile Organic Compounds*, EPA-90-FA17-03-B037, Environmental Protection Administration, Republic of China, Taiwan.
Jeon J.M., Seo B.R., Hwang I.J., Kim D.S., Kim S.D., Lee Heekwan., (2005), *Receptor Modeling Approach in IAQ Management*, Air and Waste Management Association's Annual Conference and Exhibition, 88th AWMA, Pittsburgh, United States of America, 1-9.
Jones A.P., (1999), Indoor air quality and health, *Atmospheric Environment*, **33**, 4535-4564.
Kim Y.M., Harrad S., Harrison R.M., (2001), Concentrations and sources of VOCs in urban domestic and public microenvironments, *Environmental Science & Technology*, **35**, 997-1004.
Kiurski J., Aksenitijevic S., Nedovic L., Oros I., Comic L., (2016), Influence of printing microclimate parameters on isopropyl alcohol emission, *Environmental Engineering and Management Journal*, **15**, 1705-1711.
Kopperud R.J., Ferro A.R., Hildemann L.M., (2004), Outdoor versus indoor contributions to indoor particulate matter (PM) determined by mass balance methods, *Journal of the Air & Waste Management Association*, **54**, 1188-1196.
Lee S.C., Lam S., Kin Fai H., (2001), Characterization of VOCs, ozone, and PM_{10} emissions from office equipment in an environmental chamber, *Building and Environment*, **36**, 837-842.
Lin C.Y., (2004), *Study on the effects of environmental factors to the VOCs and formaldehyde emission rates from interior building*, MSc Thesis, Department of Environmental and Occupation Health Medical College, National Cheng Kung University, Tainan, Taiwan.
Majumdar D., Patil D., Malviya R., Trivedi J., (2016), Determination of air change rates by using indoor CO as tracer: applicability and environmental issues, *Environmental Engineering and Management Journal*, **14**, 421-427.
Oh T.S., Kim M.J., Lim J.J., Kang O.Y., Shetty K.V., Sankara Rao B., Yoo C.K., Park J.H., Kim J.T., (2012), A real-time monitoring and assessment method for calculation of total amounts of indoor air pollutants emitted in subway stations, *Journal of the Air & Waste Management Association*, **62**, 517-526.
Reynolds S.J., Black D.W., Borin S.S., Breuer G., Burmeister L.F., Fuortes L.J., Smith T.F., Stein M.A., Subramanian P., Thorne P.S., Whitten P., (2001), Indoor environmental quality in six commercial office buildings in the Midwest United States, *Applied Occupational and Environmental Hygiene*, **16**, 1065-1077.
Scheff P.A., Paulius V.K., Curtis L., Conroy L.M., (2000), Indoor air quality in a middle school, Part II: Development of emission factors for particulate matter and bioaerosols, *Applied Occupational and Environmental Hygiene*, **15**, 835-842.
Seppanen O., Fisk W.J., (2001), Association of ventilation system type with SBS symptoms in office workers, *Indoor Air*, **12**, 98-112.
Sofuoglu S.C., (2008), Application of artificial neural networks to predict prevalence of building-related symptoms in office buildings, *Building and Environment*, **43**, 1121-1126.
Springston J.P., Esposito W.A., Cleversey K.W., (2002), Baseline indoor air quality measurements collected from 136 metropolitan New York region commercial office buildings between 1997-1999, *AIHA Journal*, **63**, 354-360.
Tham K.W., Zuraimi M.S., Sekhar S.C., (2004), Emission modelling and validation of VOCs' source strengths in air-conditioned office premises, *Environment International*, **30**, 1075-1088.
Wang H.C., Tseng C.H., Hsieh T.Y., (2008), *Developing an Indoor Air Quality Index System based on the Health Damage Assessment*, The 11th Int. Conf. on Indoor Air Quality and Climate, Indoor air 2008, Denmark.
Watson J.G., Chow J.C., (2005), *Air Quality Modeling: Theories, Methodologies, Computational Techniques, and Available Databases and Software Volume II-Advanced Topics-16B Receptor Models*, In: *Air & Waste Management Association*, Zannetti P. (Ed), The EnviroComp Institute Air & Waste Management Association, 455-501.
Wolkoff P., (1999), How to measure and evaluate volatile organic compound emissions from building products, *Science of the Total Environment*, **227**, 197-213.
Wong L.T., Mui K.W., (2009), Efficiency assessment of indoor environmental policy for air-conditioned offices in Hong Kong, *Applied Energy*, **86**, 1933-1938.
Wong L.T., Mui K.W., Hui P.S., (2006), A statistical model for characterizing common air pollutants in air-conditioned offices, *Atmospheric Environment*, **40**, 4246-4257.
Zuraimi M.S., Tham K.W., Sekhar S.C., (2004), A study on the identification and quantification of sources of VOCs in 5 air-conditioned Singapore office buildings, *Building and Environment*, **39**, 165-177.