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# An Adaptive Indoor Air Quality Control Scheme for Minimizing Volatile Organic Compounds Density

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**ABSTRACT** Volatile organic compounds (VOCs) such as toluene, xylene, and formaldehyde are commonly found in indoor and the VOCs will yield human health's issue. The compounds are crucial in determining the indoor air quality (IAQ) and hence being how to manage IAQ becomes an important topic. Most human may spend most of time living in poor IAQ environment and it may result in excess life risk to respiratory symptoms and billion US dollars cost annually. VOC degrades IAQ and high VOC density indoor is not uncommon. The World Health Organization (WHO) and the Government of Canada provided benchmarks on the harm levels and the benchmarks indicated the potential health risk caused by hazardous substances. In this paper, a new comprehensive control scheme, namely fuzzy genetic multi-layer control scheme (FGMLCS), is designed to manage the IAQ. The multilayer control structure is designed which includes fuzzy logic together with genetic algorithm and multi-objective optimization to give an optimal control for a better IAQ. Q factor is defined based on the "harm levels" set by the benchmarks to give a unified standard for various VOCs with different "harm levels". FGMLCS has achieved VOC density better than the "harm levels" by over 57%, which is superior to the benchmarks and is able to lower the risk of health deterioration and thus aiding habitant to be less carcinogenic.

**INDEX TERMS** Indoor air quality, volatile organic compounds, multilayer control structure, artificial intelligence, adaptive control.

## I. INTRODUCTION

Indoor air quality (IAQ) refers to the quality of the air in buildings. Improving IAQ can improve human being's health. It is found that 90% of human's living time is spent in indoor [1]. Therefore, improving IAQ is important than improving outdoor air quality. In essence, poor IAQ may result in dizziness, respiratory irritation, fatigue, asthma and allergy [2], [3]. It is trivial that long term living in poor IAQ environment may significantly increase the morbidity of cancer by 16% [1]. Poor IAQ also provokes worse effects on the pregnant, children and the elderly. More unfavorable outcome of poor

IAQ is evidenced from the low birth weight and increased preterm birth of pregnancy [4]. It is also estimated that 23% cough and 12% sputum among the elderly are potentially caused by poor IAQ problem [5].

According to the World Health Organization (WHO), 30% of newly constructed or renewal buildings provokes serious IAQ problem [6]. It is estimated that poor IAQ causes an expenditure of over \$70 billion US dollars annually including direct medical cost, loss in production [7] etc.

Volatile organic compound (VOC) degrades IAQ and high VOC density indoor is not uncommon [8]. VOCs are released as gases from certain liquids or solids. Depending on the chemical type and density of VOCs, it can cause long-term and short-term health problems. However, chemical products,

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especially organic chemicals, are always found in household products such as wax, paints and pesticides. These products can release VOCs even if they are held in store only. There are substantial scientific evidences showing adverse health effects of VOCs such as toluene, xylene, formaldehyde, etc. VOC may cause poor IAQ and thus zero VOC is an ideal target. Hitherto, it is practically impossible to reach zero VOC and hence the benchmarks standardized the “harm levels” of VOCs [1], [2].

Intuitively, it is recommended that if the VOC-emitting sources are identifiable and manageable, it is possible to directly reduce the density of indoor VOC by removing or completely sealing it. Minnesota Department of Health [9] suggested several methods to reduce human exposure to VOCs at home. One of the methods is to reduce or remove the products that release VOCs. Reduction of VOCs by using low-VOC furnishing or paints or storing unused chemicals are feasible methods. However, these methods can only alleviate the density of VOC to some extent and they cannot ensure the level of total indoor VOC is below the benchmarks. Furthermore, it is quite difficult to identify all products releasing VOCs at home or offices. Some VOC-emitting source are hard to discover such as wooden products or textiles. Hence, the department highlighted that increasing the amount of fresh air from outdoors through the ventilation system is also a feasible method to alleviate the high density of VOCs. Similarly, the American Lung Association [10] and the United States Environmental Protection Agency [11] suggested to limit the use of products that release high VOCs and make use of ventilation systems when using VOC-containing products. In short, considering the applicability of the methods, ventilation system is rather a feasible method to help in VOC control.

Numerous researches have indicated the importance of good air quality. Simone Brienza *et al.* proposed low-cost air quality monitoring system which is referred to as *uSense* which showed the concentration of pollutants in real-time around the city [12]. *uSense* was tested through an in-filed experiment and showed that it was able to share the collected data and the system was profitable. Indoor air quality monitoring (IAQM) system was proposed by Mohieddine Benammar *et al.* in which the gateway inside the system was responsible for processing the collected air quality index [13]. The modular IAQM architecture was adopted resulting in a scalable system that allowed seamless integration of wireless networks, sensing technologies and smart mobile standards. Mad Saad *et al.* proposed an IAQ monitoring scheme which is able to identify the sources influencing the air quality [14]. Salamone *et al.*, proposed a system to control the indoor environmental parameters through a designed control algorithm and hardware design [15]. Research was proposed to establish the best mounting point for gas sensors by Villa *et al.*, [16]. The results provided a guideline on how to develop an unmanned aerial vehicle system to effectively measure the source of pollutant emission.

From the previous literature, it is shown that the IAQ management is important. However, the current research mainly focused on the monitoring or hardware development for IAQ management. As the topic is closely related to human, it is better to find a good way to monitor and control the IAQ artificially. The proposed fuzzy genetic multi-layer control scheme (FGMLCS) is designed with the objective of IAQ monitoring and control artificially. By controlling the “harm levels” of the VOC, the short-term health problem may be alleviated and respiratory risk can also be reduced. The contributions of this work are summarized as: (1) Fusion of genetic algorithm (GA) and fuzzy logic (FL) to build the constraint direct control layer (CDCL) was developed. (2) Q factor is defined to reflect the VOC problem based on the “harm levels” set by the benchmarks [1], [2]. (3) FGMLCS cooperated with the CDCL was developed and result indicated that FGMLCS achieved a better IAQ performance in terms of VOC reduction by 57%.

The rest of the paper is organized as follows, Section II provided the background of methodology that related to the development of FGMLCS. Section III explained the details of FGMLCS. Section IV showed the performance of the FGMLCS. Section V showed a conclusion of this work.

## II. BACKGROUND OF METHODOLOGY

To give human a comfort indoor environment and improve the IAQ, a new control scheme, FGMLCS, is developed for IAQ management. It trades off environmental parameters such as humidity, temperature, and IAQ. FGMLCS not only considers the density of total VOC, but also analyzes the individual VOC elements such as formaldehyde, xylene, and toluene. Attention is drawn to the fact that even at a low density of total VOC, it is still harmful to human health.

Conventional control method mainly focused on the direct control layer (DCL) in the previous works [4], which directly controls the operation process with a real-time control management by considering the input from the Process layer  $i_t$  and give a controlled output  $o_t$ , shown as Fig. 1. However, one feedback loop by DCL only provides basic control process where adaptive characteristics and accuracy are unclear without constraints limitation. As a result, the control performance of the system cannot be optimized.

Therefore, in order to give a better control performance, multi-layer control system (MCS) is built. MCS [17], [18] is a control structure built on the plant (i.e. the operation process of the system) which can be expressed as the realization of several partial achievements [19].

In practice, MCS mainly includes the Process layer, DCL and optimization layer (OPL). The OPL solves the customized problem and delivers the optimal control parameters to DCL. Optimization in MCS maximizes the product value as well as minimizes the product costs over a long-time horizon. With accurate and adaptive performance on the control process, MCS is a good control system. As a result, it can provide efficient and optimal control performance to the IAQ management system.

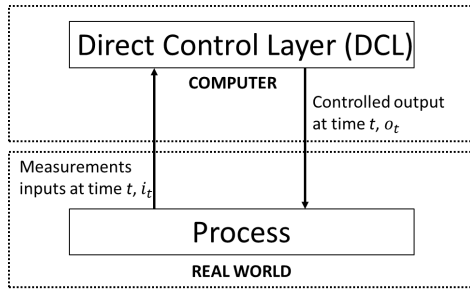


FIGURE 1. Direct control loop (DCL) operation structure [4].

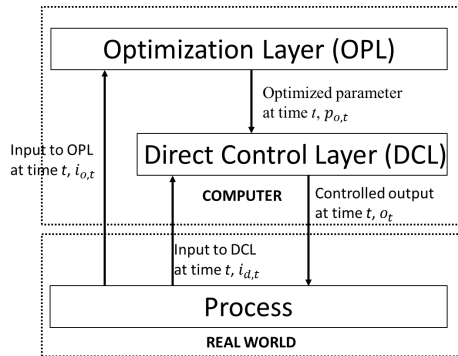


FIGURE 2. Generic structure of multi-layer control system (MCS).

The input from the plant can be classified into two types based on the direction of the destination layers,  $i_{d,t}$  and  $i_{o,t}$ .  $i_{d,t}$  is the input into DCL for direct control to the plant. To give a real-time and adaptive control management, the control loop between DCL and the plant is very short, usually in ms. To increase the control efficiency, it is better to define a new layer referred as CDCL where the constraints can be set to give a more accurate performance and the details of CDCL will be discussed in Section III. At the same time, optimization layer requires  $i_{o,t}$  to generate optimal settings of different parameters  $p_{o,t}$  to maximize the control efficiency. The final output in DCL will consider  $i_{d,t}$  as well as the optimized parameters  $p_{o,t}$  to generate the output. Finally, the output of DCL is then transmitted to the plant to control the physical equipment to implement the control command. When real time control command is considered, a fast and simple-programming algorithm like GA should be adopted as the backbone algorithm for the control system. Fusion of FL and GA can combine their strength as well as reduce their limitations [20].

Because of multiple criteria, multiple objectives should be considered instead of single objective. Besides, in engineering related areas, finding global optimal solution may not be the answer to be obtained compulsorily. Fast, adaptive and accurate output are more favorable as long as fulfilling the requirement. NSGA-II is a multi-objective optimization algorithm with fast convergence and large diversity, and hence has a leading performance on solving the practical engineering problems.

To keep all the individual VOC density at a safe level, Q factor is defined in optimization layer based on the “harm

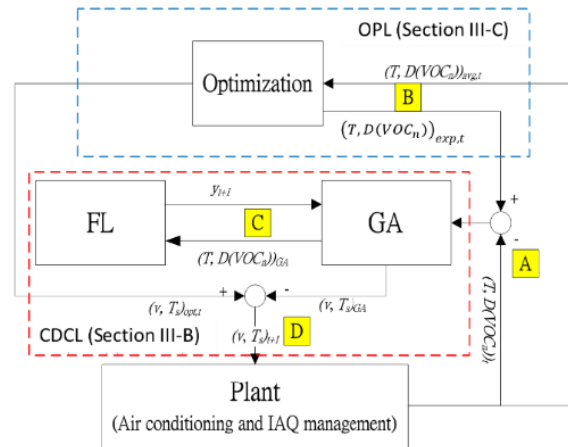


FIGURE 3. Structure of FGMLCS.

levels” set by the benchmarks [1], [2]. By considering Q factor, various VOCs with different “harm levels” can be treated with a unified standard. Besides, the situation can be prevented when the density of a particular VOC is low in value while it exceeds the harm levels. It will be explained in Section III.

The development of FGMLCS is based on the advanced MCS to facilitate the performance of IAQ control with minimum cost. In FGMLCS, FL and GA are adopted as the main backbones. NSGA-II is customized for IAQ control in the optimization layer to further optimize the indoor environment conditions and minimize the VOC density.

### III. NEW MODEL FGMLCS DESIGN - DETAILS

#### A. STRUCTURE OF FGMLCS

In order to improve the IAQ, the new control scheme, FGMLCS, is developed for IAQ management. FGMLCS not only considers the density of total VOCs, but also analyzes the individual VOC elements such as formaldehyde, acetaldehyde, xylene, toluene and styrene. It is necessary to consider various VOCs because even with a low density of total VOC, it still cannot prevent the exceeding of individual VOC, which is still harmful to human health.

In this paper, MCS is further developed and customized with FL and GA to form a new control system referred as FGMLCS which can be applied in IAQ management. The structure of FGMLCS is shown in Fig. 3. Conventionally, to give a real-time and adaptive control management, the control loop between DCL and plant are usually represented in unit of millisecond. To improve the efficiency of the entire control process, it is better to define a new layer called constraint direct control layer (CDCL) where FL and GA are applied to control the environmental parameter settings. The output from CDCL is then transmitted to the plant to control the physical equipment in order to implement the control command.

1. T - indoor temperature
2.  $D(VOC_n)$  - indoor density of VOCs

3.  $v$  - ventilation speed
4.  $T_s$  - temperature setting

The whole control process in the control scheme FGMLCS can be divided into four parts, shown as “A”, “B”, “C” and “D” as indicated in Fig. 3, and the details of each part are:

**Part A:** The average indoor temperature  $T$  and averaged VOCs density up to time  $t$ ,  $(T, D(\text{VOC}_n))_{\text{avg},t}$  is regarded as the input of OPL. The output of OPL is divided into two types: output to plant  $(v, T_s)_{\text{opt},t}$  to affect the output of the CDCL  $(v, T_s)_{t+1}$ ; and the expected environmental parameters  $(T, D(\text{VOC}_n))_{\text{exp},t}$  which will be compared with  $(T, D(\text{VOC}_n))_t$  at time  $t$ . Ideally, what is expected is the equality between the two, which is

$$(T, D(\text{VOC}_n))_t = (T, D(\text{VOC}_n))_{\text{exp},t} \quad (1)$$

The difference between  $(T, D(\text{VOC}_n))_t$  and  $(T, D(\text{VOC}_n))_{\text{exp},t}$  is treated as the input of CDCL.

**Part B:** Environmental parameters such as  $(T, D(\text{VOC}_n))_t$  are averaged up to time  $t$  to be the input of OPL. OPL will generate an optimized  $(T, D(\text{VOC}_n))_{\text{exp},t}$  based on multi-objective optimization method. The optimized  $(T, D(\text{VOC}_n))_{\text{exp},t}$  is then used to compare with the  $(T, D(\text{VOC}_n))_t$ . The operation in OPL will be explained in sub-section C “DEVELOPMENT of OPL”.

**Part C:** Fusion of FL and GA can combine their strength as well as reduce their limitations and the related detailed methodology formulation and explanation will be given in next sub-section “DEVELOPMENT of CDCL”.

**Part D:** The output of GA  $(v, T_s)_{\text{GA}}$  will be used to calculate the difference with  $(v, T_s)_{\text{opt},t}$  to generate the output  $(v, T_s)_{t+1}$ . Besides, the ventilation speed ( $v$ ) and temperature setting ( $T_s$ ) of the air conditioner are considered as control variables. The system reacts based on the state variables at time  $t$  to determine the action taken at time  $t+1$  and the state equations is formulated as:

$$\frac{dT(t)}{dt} = \frac{\delta Q_{\text{outdoor}}}{c_o m_{\text{indoor}}} \quad (2)$$

where  $c_o$  refers to specific heat of indoor air and  $m_{\text{indoor}}$  is the estimated mass of the indoor air.  $\delta Q_{\text{outdoor}}$  denotes the infinitesimal increment of heat supplied to the indoor system from outdoor. For notation simplicity,  $D(\text{VOC}_n)$  is denoted by  $D_v$ , which represents for state equations for each VOC component.

$$\frac{dD_v(t)}{dt} = D_v(t) \cdot \frac{m_{\text{indoor}}}{m_{\text{indoor}} + v \cdot s \cdot \rho_0} + D_{v,\text{outdoor}} \cdot \frac{v \cdot s \cdot \rho_0}{m_{\text{indoor}} + v \cdot s \cdot \rho_0} \quad (3)$$

where  $v$  refers to the ventilation speed,  $s$  is unit of time,  $\rho_0$  is the mass of air per meter and  $D_v(t)$  is the density of indoor VOCs at time  $t$ ,  $\delta m_{\text{indoor}}$  refers to infinitesimal increment of the mass of indoor air and  $D_{v,\text{outdoor}}$  can be regarded as a constant, which is the outdoor density of VOCs.

## B. DEVELOPMENT OF CDCL

In this paper, CDCL is developed to generate an optimized control for process to operate. In detail, CDCL provides constraint settings which ensure the robustness and accuracy of the system and thus the system can perform a stable and adaptive control process with the variation of the parameters. Under such a condition, FGMLCS ensures the control system to achieve the required features of the process outputs or limits the outputs within a range of acceptable values.

Feedback control systems are used to keep the controlled variables as close as possible to the reference values which further ensures the robustness of the control system. Classical approaches to select feedback control algorithm is to identify a linear process model and then choose a linear control algorithm to solve the problem. However, for IAQ management, linear process model may not be sufficient to reflect the IAQ problem, which is a nonlinear problem. Therefore, FL, a control algorithm coping with nonlinear control process, is a choice in IAQ management as the constraint control layer in FGMLCS.

A combination of GA and FL is designed in CDCL to prevent the limitations of both GA (i.e. premature convergence) and FL (complex training of membership function design) [16]. As shown in Fig. 3, the difference of  $(T, D(\text{VOC}_n))_{\text{exp},t}$  and  $(T, D(\text{VOC}_n))_t$  is measured as input of CDCL. It is necessary to mention that if  $(T, D(\text{VOC}_n))_t$  reaches the expected values  $(T, D(\text{VOC}_n))_{\text{exp},t}$ , there is no input into CDCL.

After fuzzification, a status parameter,  $y_{t+1}$ , which can reflect the human comfort standards, will be also regarded as a key variable in GA to give a final decision (temperature and ventilation of time  $t+1$ ).

FL is applied to provide a human comfort performance for FGMLCS. The membership function design of the inputs is shown in Table 1. Firstly, the membership function design is trained based on the data collected from various buildings such as shopping malls, apartments and universities. Secondly, the design of membership functions considered the key concept that the output should be robust and keep in a low VOC density as low as possible.

As shown in Table 1, the membership function for each class (L,LC,C,UC,U) means the typical values for the tropizontal functions with (L=lower\_bound, LC=lower\_bound\_for\_the\_center, C=center, UC=upper\_bound\_for\_the\_center, U=upper\_bound). The output of FL,  $y_{t+1}$ , is a weighting factor for  $T_s$  and  $v$ .

## C. DEVELOPMENT OF OPL

In order to achieve an optimal control with maximum system performance and minimum product costs, a trade-off optimal solution for all the objectives is more favorable. Multi-objective optimization, which can provide trade-off optimal solutions to multiple objectives, is a good candidate method for the optimization layer in FGMLCS. The multi-objective problems render the launch of multi-objective evolutionary algorithms (MOEAs). The MOEA is a kind of optimization

TABLE 1. Design of membership for FL.

Input Description	Low class	Medium class	High class
Indoor temperature	(16, 18, 20, 24, 26)	(22, 24, 26, 28, 30)	(26, 28, 30, 32, 34)
Formaldehyde	(0, 0.02, 0.04, 0.06, 0.08)	(0.04, 0.06, 0.08, 0.1, 0.1)	(0.06, 0.08, 0.1, 0.12, 0.16)
Acetaldehyde	(0.02, 0.04, 0.06, 0.08, 0.1)	(0.04, 0.06, 0.08, 0.1, 0.12)	(0.08, 0.1, 0.13, 0.15, 0.17)
Xylene	(0, 0.03, 0.05, 0.07, 0.09)	(0.05, 0.07, 0.11, 0.13, 0.15)	(0.07, 0.011, 0.15, 0.17, 0.2)
Toluene	(0, 0.01, 0.03, 0.05, 0.07)	(0.02, 0.04, 0.06, 0.08, 0.1)	(0.03, 0.05, 0.07, 0.09, 0.11)
Styrene	(0.03, 0.05, 0.07, 0.09, 0.11)	(0.05, 0.07, 0.09, 0.11, 0.13)	(0.07, 0.09, 0.11, 0.13, 0.16)
Output $y_{t+1}$	(0, 0.05, 0.2, 0.35, 0.5)	(0.2, 0.35, 0.5, 0.65, 0.8)	(0.5, 0.65, 0.8, 0.95, 1)

that always searches for a set of nondominated optimal solution which is referred as pareto-front (PF) [21]. Moreover, it is well evidenced that nondominated sorting genetic algorithm II (NSGA-II) is proven to outperform other MOEAs in terms of convergence and diversity functional analysis [22]. Thus NSGA-II [23] is employed in this paper for custom design of OPL in FGMLCS.

In this case, objectives are designed as: minimize the total VOC density; minimize typical VOC component (formaldehyde, acetaldehyde, xylene, toluene and styrene).

As a result, the objective functions of NSGA-II are

$$\begin{aligned} \text{MIN } F_1 &= \sum_{i \rightarrow n} D(VOC_i) + (v_{VOC} - v) \cdot t & (4) \\ \text{MIN } F_2 &= \text{MAX}(\{Q_{VOC} | j = \text{formaldehyde,} \\ &\quad \text{acetaldehyde, xylene, , toluene and styrene}\}) \\ \text{s.t. } v &\in [0, v_{max}] & (5) \end{aligned}$$

where  $D(VOC_i)$  is the density of individual VOCs.  $t$  refers to the time period between each two adjacent operation of OPL.  $v_{VOC}$  is the emission speed of the individual VOCs.  $Q$  factor for VOC,  $Q_{VOC}$ , is defined in this paper, which is

$$Q_{VOC} = \frac{D(VOC)}{D(VOC_{standard})} \tag{6}$$

where  $D(VOC_{standard})$  is the standard ‘‘harm levels’’ set by WHO [1]. In detail,  $D(VOC_{standard, formaldehyde}) = 0.1 \text{ mg/m}^3$ ;  $D(VOC_{standard, xylene}) = 0.447 \text{ mg/m}^3$ ;  $D(VOC_{standard, acetaldehyde}) = 0.28 \text{ mg/m}^3$ ;  $D(VOC_{standard, toluene}) = 0.392 \text{ mg/m}^3$  and  $D(VOC_{standard, styrene}) = 0.85 \text{ mg/m}^3$ . The five VOCs were chosen for experiment as they are the indicative VOCs [1], [2] affecting people’s health status.  $Q$  factor ( $Q_{VOC}$ ) provides a unified standard of various VOCs with different ‘‘harm levels’’, which thus can be considered by the control system to provide a more reliable performance. There are two potential advantages to define  $Q$  factor ( $Q_{VOC}$ ):

(i) The energy consumption maybe reduced with the consideration of normalized VOC density. For example, without normalization based on  $D(VOC_{standard})$ , when the density of xylene is  $0.3 \text{ mg/m}^3$ , the ventilation speed may be

the same as the condition of formaldehyde density at  $0.3 \text{ mg/m}^3$ . However, with the same density as  $0.3 \text{ mg/m}^3$  of both formaldehyde and xylene, the  $Q$  factor,  $Q_{VOC}$ , are 3 for formaldehyde and 0.67 for xylene respectively. Therefore, the ventilation speed may be reduced for the case with xylene density as  $0.3 \text{ mg/m}^3$  and the harmful extent will still remain low to human body (i.e. better than ‘‘harm levels’’ by the benchmarks [1], [2]) while the energy consumption will be reduced.

(ii) The situation can be prevented when the real density of particular VOC is low in value while it exceeds the harm levels. For example, when the density of formaldehyde reaches  $0.3 \text{ mg/m}^3$ , it exceeds the ‘‘harm level’’ ( $0.1 \text{ mg/m}^3$ ) by two times and dizziness may be caused even with a short term staying. In contrast, when the density of xylene is  $0.3 \text{ mg/m}^3$ , it is still within the ‘‘harm level’’. As a result,  $Q$  factor is defined based on  $D(VOC_{standard})$  set by the benchmarks.

#### IV. PERFORMANCE EVALUATION

In order to give an analysis of the IAQ management performance provided by FGMLCS, experimental testing was implemented. Schematic diagram is shown in Fig. 4.

As shown in Fig. 4, the experimental testing included four parts: 1) Sensors: Various types of sensors were used for collecting data such as temperature, humidity, VOCs; 2) Ventilation device: The device is used to manage the indoor wind speed depending on the density of VOCs; 3) Controller: Output of controller was used to alter the wind speed by analyzing the data collected by sensors; 4) ZigBee: as the communication protocol due to its mesh network and low energy consumption capabilities. Based on the schematic diagram, a small-scale experimental testing was designed, which is shown in Fig. 5.

A small-scale experimental testing was first designed to evaluate the performance of FGMLCS. A unit volume of environment was adopted for simplifying the control process [24]. Besides, such a unit volume also simplifies the scalability testing.

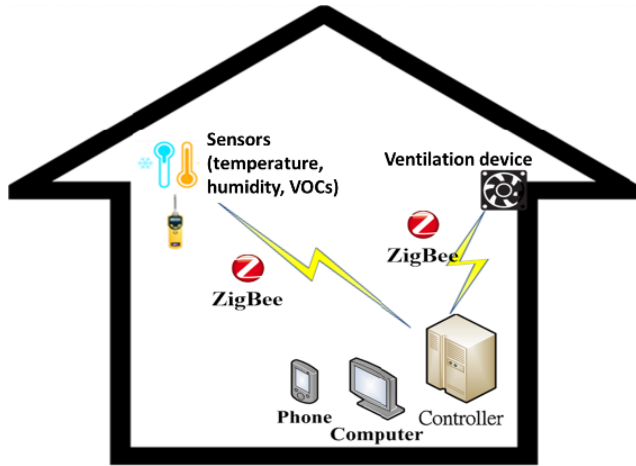


FIGURE 4. Schematic diagram of the experimental testing.

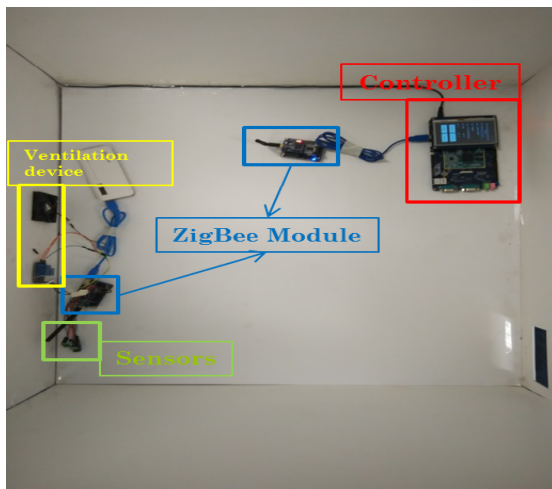


FIGURE 5. Small-scale experiment set up.

Initially, the density of all of the five typical VOCs (formaldehyde, acetaldehyde, toluene, xylene and styrene) were set as  $1 \text{ mg/m}^3$  (i.e. unit density) to provide a harmful environment.

Furthermore, the density of the five VOCs was exceeded the standard harm levels (formaldehyde:  $0.1 \text{ mg/m}^3$ , acetaldehyde:  $0.28 \text{ mg/m}^3$ , xylene:  $0.447 \text{ mg/m}^3$ , toluene:  $0.392 \text{ mg/m}^3$ , styrene:  $0.85 \text{ mg/m}^3$ ). The measuring device of VOCs was ppbRAE3000, which was proved to be an advanced device for IAQ management and had been widely adopted as the measuring device by academic and industrial institutions [25].

Figure 6 shows the density of individual VOCs for 24 hours. The dotted line corresponds to the harm levels of each VOC. Fig. 6 shows the density of each measured VOC during the experiment. For example, the density of formaldehyde shown in Fig. 6 dropped the most significantly and the harm level for it was  $0.1 \text{ mg/m}^3$ . Similarly, other VOCs dropped with various speed shown in Fig. 6.

As shown in Fig. 6, after initialization, the density of all the VOCs dropped significantly in the first hour because they

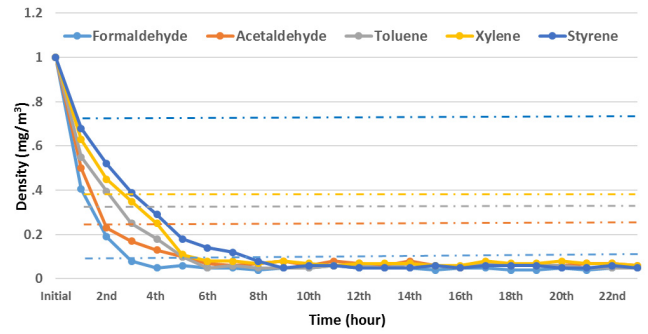


FIGURE 6. Density of VOCs with  $1 \text{ mg/m}^3$  initially.

all exceeded the standard harm levels by more than 53%. One hour later, the measured VOC density dropped slower than the first hour. That was caused by OPL in FGMLCS. OPL provided an optimal solution based on multi-objective optimization method. The difference between the current VOC density ( $D(\text{VOC}_n)_t$ ) and ( $D(\text{VOC}_n)_{\text{exp},t}$ ) became the input into CDCL. Therefore, when the difference is smaller, the ventilation speed obtained by CDCL will be reduced.

Moreover, as shown in Fig. 6, the dropping speed (i.e. slope of the curves) varies with different individual VOCs. The reason for the different dropping speed of individual VOCs is normalization of the VOC density. With the same density, the individual VOC with smaller standard “harm level” (i.e. more toxic) will be dealt with first. For example, the standard harm levels of formaldehyde is  $0.1 \text{ mg/m}^3$  while styrene is  $0.85 \text{ mg/m}^3$ . After normalization, the normalized density of formaldehyde ( $Q_{\text{VOC,formaldehyde}}$ ) is 10 at initialization stage (i.e. real density is  $1 \text{ mg/m}^3$ ). Similarly,  $Q_{\text{VOC,styrene}}$  is 1.2 initially with the real density as  $1 \text{ mg/m}^3$ . As a result, based on (5), the dropping speed of formaldehyde is the fastest amongst the five individual VOCs. On the other hand, styrene drops the slowest with the least harm level among other VOCs.

It is necessary to mention that because of the furniture and construction materials release VOCs all the time. As a result, with the consideration of the model build based on (4), if FGMLCS was not applied after 10 hours in Fig. 6 (i.e.  $v$  in (4) is 0), total VOC density would increase continuously. That is the reason why the ventilation speed in FGMLCS considers the releasing speed of VOCs from furniture and construction materials. Furthermore, as the releasing speed of VOCs varies with the change of temperature and humidity [6], even after reaching a relatively stable status, it is necessary to apply FGMLCS to keep VOC in low density low in a changeable environment.

With the assistance of normalized VOC density, the ventilation speed will be relatively smaller after 3 hours initialization. After 6<sup>th</sup> hour, the improvement for formaldehyde is 57%, acetaldehyde is 75%, 93% for xylene, 87% for toluene and 83% for styrene compared with the benchmarks [1], [2]. The improvement has a great potential benefit to human health as the main objective is to keep the density of VOCs

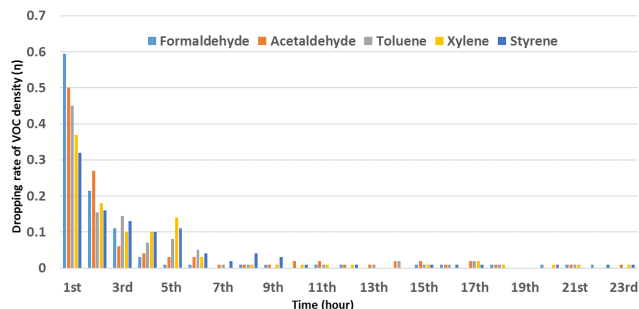


FIGURE 7. The dropping rate ( $\eta$ ) trend against the ventilation time.

as low as possible. Taking formaldehyde as an example, it is an inevitable VOC as it is emitted from furniture, wooden products, textiles or detergents [1]. Hence, the benchmarks provided a reference for people to understand whether an indoor environment is harmful or not. The provided benchmark is set based on people staying the indoor environment for a time < 24 hours. Hence, from the perspective of people, it is better to keep the VOC as low as possible as the final goal of IAQ is to provide a free VOC environment for people. In brief, the proposed scheme can alleviate the VOC density and it is expected to reduce the occurrence of dizziness, respiratory irritation or fatigue due to VOC. Figure 7 shows the dropping rate ( $\eta$ ) of VOCs according to the density, which is defined as

$$\eta = \frac{|D(VOC_n, t) - D(VOC_n, t - \Delta t)|}{\Delta t} \quad (7)$$

$D(VOC_n, t)$  and  $D(VOC_n, t - \Delta t)$  refers to the dropping rate of the  $VOC_n$  density between the time period  $\Delta t$ . Generally,  $\eta$  deteriorates with the decreasing density. It is necessary to mention that initially the VOCs density is relatively high, which leads to a significantly increased  $\eta$  to weaken the health status caused by the high VOC density. And,  $\eta$  is reversely proportional to the standard “harm levels” set by the benchmarks. The objective of the Figure 7 is to demonstrate when the VOC density will drop significantly. As from (7), the dropping rate ( $\eta$ ) is the difference of a VOC within a time interval. The higher the dropping rate of a VOC, the more reduction on the VOC within the time interval. After the proposed scheme was launched for 6 ~ 7 hours, the dropping rate became hard to read compared with first or third hour. This is because the difference between the rate of VOC emission and the rate of sending VOC (by ventilation fan) is very close. Hence, the dropping rate lined between zero and  $0.01 \text{ mg/m}^3 \cdot \text{s}$  after launching the scheme from 6 ~ 7 hours.

Furthermore, Fig. 8 shows the trend of  $\eta$  against Q factor and the density of the VOC.

As shown in Fig. 8,  $\eta$  increases significantly with a linearly increased  $D(VOC_n)$ . For example,  $\eta$  equals to  $\sim 0.58$  when  $D(VOC_{\text{formaldehyde}}) = 1 \text{ mg/m}^3$ , while the value of  $\eta$  decreases significantly as  $\sim 0.23$  when  $D(VOC_{\text{formaldehyde}})$  drops to  $0.4 \text{ mg/m}^3$ . Besides,  $\eta$  is also

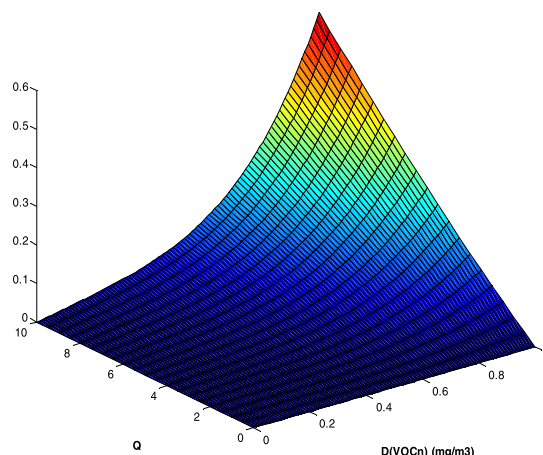


FIGURE 8. Trend of  $\eta$  against Q and  $D(VOC_n)$ .

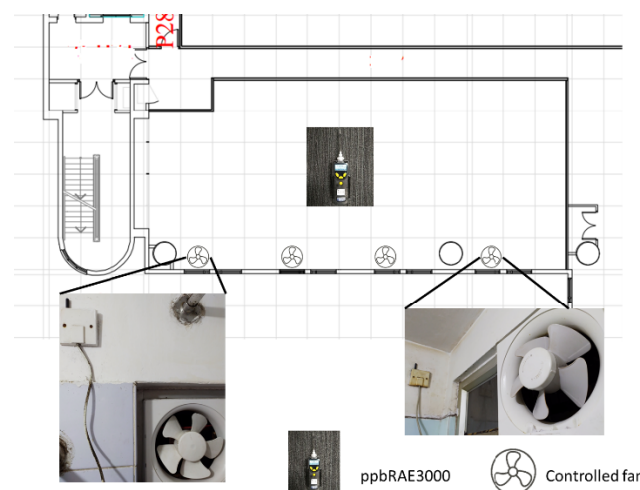
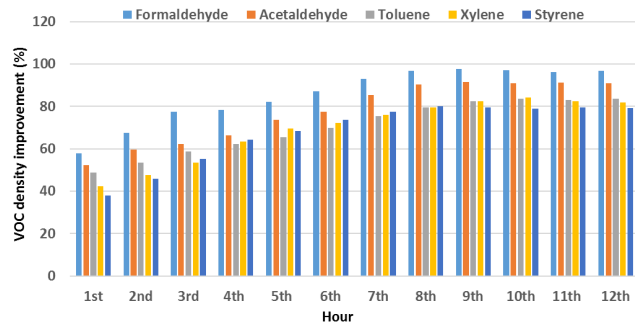


FIGURE 9. Experimental setup for validation of the proposed scheme in building.

affected by Q factor. An increased Q also enlarges the numerical value of  $\eta$ . For instance,  $Q_{\text{formaldehyde}} = \sim 10$  (with  $D(VOC_{\text{formaldehyde}})_{\text{standard}} = \sim 1 \text{ mg/m}^3$ ) and  $Q_{\text{xylene}} = \sim 2.2$  (with  $(VOC_{\text{xylene}})_{\text{standard}} = \sim 0.44 \text{ mg/m}^3$ ) when their density both reaches  $1 \text{ mg/m}^3$ . Accordingly,  $\eta_{\text{formaldehyde}} = \sim 0.59 \text{ mg/m}^3 \cdot \text{s}$  and  $\eta_{\text{xylene}} = \sim 0.38 \text{ mg/m}^3 \cdot \text{s}$ . Hence, it is shown that the developed FGMLCS has an outstanding performance in IAQ management.

The small-scale experiment experimental testing was then extended to an indoor environment of 20 meters \* 9 meters. The VOC monitor ppbRAE3000 was placed at the center of the area and there were four fans in the area. The ventilation speed of the fans was controllable. Figure 9 shows the floor plan of the area and the location of the fans. In this experiment, the VOCs of the area were measured through the VOC monitor. The measured data was then used to obtain the optimized ventilation speed through the proposed scheme. Finally, the ventilation speed was changed in order to alleviate the density of VOCs. In order to show the effectiveness of the proposed scheme in the area, Figure 10 is shown.



**FIGURE 10. VOC density improvement after using the proposed scheme in the building.**

Figure 10 shows the VOC density improvement after using the proposed scheme for 12 hours.

As shown in Fig. 10, the VOC density has a significant improvement in the first hour. For formaldehyde, the percentage improvement reached 57.8% and 37.8% for styrene. Before the eighth hour of the experiment, the improvement of VOC density increases at a steady trend as the density of VOC was still relatively high. It is observed that from the eighth hour, the percentage of improvement is relatively stable. This is because the rate of indoor VOC emission is comparable to the rate of sending VOC (by the four fans) out of the building at eighth hour. The net volume change of indoor VOC is close to zero. At eighth hour of the experiment, the density of formaldehyde, acetaldehyde, toluene, xylene and styrene are  $0.04 \text{ mg/m}^3$ ,  $0.09 \text{ mg/m}^3$ ,  $0.07 \text{ mg/m}^3$ ,  $0.07 \text{ mg/m}^3$  and  $0.15 \text{ mg/m}^3$  respectively. After the eighth hour, the density of the VOCs did not change significantly. From the indoor experiment, the scheme was proved successfully because the scheme help reducing the density of VOCs obviously.

## V. CONCLUSION

Indoor Air Quality (IAQ) becomes a serious problem with the modernization of urban development as it can cause extra risk of respiratory system and billion US dollars cost annually. VOC degrades IAQ and high VOC density indoor have been observed frequently. In this paper, to improve IAQ and indoor environmental comfort, a new comprehensive control scheme is developed and referred as FGMLCS. The contributions of the paper is three-folded. (1) Fusion of GA and FL to build the Constraint Direct Control Layer (CDCL) was developed. (2) Q factor is first-time defined to reflect the VOC problem based on the “harm levels” set by the benchmarks (3) FGMLCS cooperated with the CDCL was developed and result indicated that FGMLCS achieved a better IAQ performance in terms of VOC reduction by over 57% compared with the benchmarks. Hence, FGMLCS is effective in managing IAQ and be able to lower the risk of respiratory health caused by poor IAQ problem.

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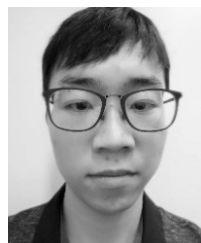
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