CO Multi-Forecasting Model for Indoor Health and Safety Management in Smart Home

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Abstract

The integrated application of the Internet of Things and artificial intelligence (AIoT) is key during the developmental process from a smart home to smart city and the design of sensors for collecting various types of data is the foundation for establishing the entire AIoT. In this study, we placed our self-designed carbon monoxide (CO) sensor into a 1:10 ratio acrylic house model and simulated three types of CO hazard scenarios. The results comparing 10 cases were used to establish an innovative CO Multi-Forecasting Model (CMFM). The CMFM is suitable for application in the semi-supervised learning - based AIoT. In addition to having a 3-7 times better safety warning time compared to that of commercially available CO sensors, our CO sensor also possesses a health warning function for indoor air quality.

Keywords: Smart home, Carbon monoxide poisoning, Sensor, Artificial intelligence, Prediction

1 Introduction

In addition to health problems, carbon monoxide (CO) concentrations in the home are also a safety problem. People often spend more than 90 % of their time indoors. Therefore, Indoor Air Quality (IAQ) has important effects on people's quality of life [1]. CO poisoning results in high mortality and is highly damaging to the human body. Thus, many countries have paid attention to its public health and safety problems [2]. The cause of CO lethality and damage is that CO has a higher affinity for hemoglobin compared to the of oxygen (O_2), resulting in CO substituting for large amounts of oxygen in hemoglobin molecules, causing blood oxygen concentrations to drastically decrease [3]. The length and concentration of CO exposure will result in dizziness, nausea, vomiting, limb weakness, somnolence, or even tissue hypoxia and injury or necrosis. CO-induced poisoning has high incidence and mortality [4]. The common reason for CO poisoning at home is incomplete combustion. After CO inhalation, tissue and cell necrosis will occur, as CO has a greater oxygen carrying capacity than that of hemoglobin. Studies have showed that the amount of CO inhaled will determine how CO toxicity affects the human body and the amount of CO inhaled is determined by the minute ventilation, exposure duration, and relative concentration of CO and O_2 in the environment [5]. Exposure to CO in the environment tends to induce cardiovascular disease and other diseases [6]. In addition to poisoning, CO will also result in IAQ-related symptoms such as sick building syndrome [7].

In Taiwanese homes, CO poisoning frequently occurs. The main reason for this is the use of water heaters, gas stoves, or coal in enclosed or poorly ventilated spaces, resulting in incomplete combustion of carbon–oxygen compounds. In homes, common CO poisoning events are a result of inappropriate usage of water heaters, incomplete combustion when gas stoves are used in the kitchen, or suicide. CO poisoning events resulting from insufficient ventilation when gas water heaters are used during bathing are frequent. The most common problem is poor ventilation at the site where the water heater is installed or a lack of safety consciousness in the user who closes the windows and doors, resulting in incomplete combustion and CO production. CO accumulates to high concentrations within a short period, leading to a safety hazard. According to statistics by the Taiwanese government, 54 CO poisoning events occurred in 2018, killing 11 people and injuring 171 people. The main cause is insufficient ventilation when water heaters are installed outside the house (70.4 %) and exhaust pipes that are not installed for water heaters according to regulations (22.2 %) [8]. The problem of home CO poisoning has continuously occurred every year. In the development

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of smart home and smart city, most of the CO monitoring applications are used to monitor indoor air quality [9-10]. If we combine real-time CO monitoring, warning and alarm with smart homes, it should be able to effectively take these safety issues into account and prevent CO poisoning in the home environment. Therefore, the current issue of accuracy and effectiveness of indoor CO monitoring cannot be ignored.

In 2011, Taiwan promulgated the Indoor Air Quality Act. According to this act, the mean indoor CO concentration over 8 hours should not exceed 9 ppm [11]. Currently, commonly seen CO alarms in the Taiwanese market mostly comply with US standards (UL2034) [12], which are divided into three stages: exposure at 70 ppm for more than 60 minutes, exposure at 150 ppm for more than 10 minutes, and exposure at 400 ppm for more than 4 minutes. An alarm will sound under these three situations. The aforementioned warning methods will mainly sound the alarm when CO is maintained at a certain concentration for a specific duration. Although the conservative alarm systems will aid in preventing wrong alarms from sounding and prevent a Type II error, they may ignore two important problems: The first is that elderly persons, weak persons, pregnant women, and young children will have a different tolerance to cumulative CO exposure and conservative control of safety problem may sacrifice opportunities for management warnings for health hazards because of low exposure. The second problem is that when differences in indoor environmental conditions result in non-stable CO concentrations, the sensor may show a delayed warning or no warning when there should be one, which is analogous to a Type I error. Therefore, how to design more precise and effective indoor CO hazard prediction models that can provide early warning in the “health prediction model,” which is used for health management, and the “safety prediction model,” which is used for integrated disaster management, are topics that are worthy of examination as in the CO Multi-Forecasting Model (CMFM) of this study.

Regarding the design of intelligent prediction and monitoring of IAQ based on all big data from smart home to smart city, benefits expansion can also promote creative commercial models and service markets through big data analysis in addition to the management of health and safety goals. The combination of general commercial company models and real-time external data and internal information for analysis can aid the promotion of decision making by companies in a dynamic and changing environment [13]. Regarding data collection, huge information feedback benefits can be obtained if wearable health sensors are used to obtain various types of scenario information at different sites and environments at any time and any place in combination with big data analysis in the healthcare system [14].

Currently, there are few smart-home related studies on the innovative design of CO sensors and their application analysis. In addition, more than one-half of the system warning determination methods refer to general commercial sensor standards in practice and lack numerical analysis, prediction, and multi-management models. An example is the establishment of health and safety management models based on different user attributes or even the application of CO sensors in AIoT. Sensor plays an important role in the application of AIoT. The Sensor must meet the characteristics of flexibility, security, real-time and low power [15]. In order to make the CO sensor suitable for the concept of AIoT, this study designed a CO sensor that can support the requirements of AIoT characteristics, and an innovative CO Multi-Forecasting Model. The CMFM has four early warning phases, from health and safety warning to physiological safety warning. In the future, the integration of AIoT through community or government will help to monitor and manage the risk of health and safety of people in indoor CO concentration from Smart Home to Smart City.

2 Literature Reviews

2.1 Smart Home

With the development of Information, Communication and Technology and the lower costs, electronic devices and the Internet have become more and more popular, which indirectly has increased the market acceptance of smart homes [16]. IoT is used in many areas of life such as smart cities, smart grids, smart homes, e-health, asset management, logistics and building performance management [17-19]. For example, air quality management and monitoring issues are often applied to Smart home planning through IoT technology [20]. In addition, the use of AIoT combined with artificial intelligence in Smart Home has also begun to attract attention in recent years, from energy management [21] to the application of combined wearable devices [22]. The combination of AI’s prediction and decision-making can significantly improve the comfort level and happiness of human life [23]. In summary, home health and safety issues combined with AIoT management is also one of the important development trends of smart home in the future. Therefore, how to use the instant monitoring system and support the information transmission and analysis application of AIoT can help early warning or prevention before the hazard occurs. This is also the main purpose of this study to propose CMFM to meet the application in AIoT.

2.2 Indoor Health and Safety

In residential buildings with poor air quality and less ventilation, sick building syndrome is 30-200 % higher than normal [24], CO, NO_2 and SO_2 are the main gas pollutants, which are also important factors for acute respiratory diseases, and CO is also one of the main sources of pollution in indoor air [25]. In the 17 state studies in the United States from 2005 to 2014, The residence is the location of the most common CO hazard event, and more than 78 % of people in need of medical care and hospitalization in the event of a hazard [26]. CO poisoning can cause headaches, dizziness, nausea, vomiting and even lead to death [27]. The use of cooking utensils at home is the easiest to raise carbon monoxide in short term. In the experiment, the CO concentration often exceeds 9 ppm, so the increase in CO concentration is not an accidental probability [28]. However, 90 % of CO poisoning cases were inadvertently exposed to CO, and 3.8 % of sequelae occurred after medical treatment [29]. Therefore, from a health or safety perspective, common but easily overlooked home CO poisoning problems require a more effective and immediate intelligent monitoring and management system to respond.

2.3 CO Sensor vs. Forecasting Model

CO monitoring has always been an important item in indoor air quality management systems. For example, the iAir system measures various indoor air pollutants with mobile monitoring software, and its CO metal oxide semiconductor sensor transmits signals to mobile devices via Wi-Fi [30]. In addition to indoor air quality, CO sensors are often used as alarm devices for carbon monoxide and fire. After the passage of NYC's CO alarm law in New York City, the number of non-fire CO poisoning and deaths fell by 25 % and 50 % [31]. The water heater is one of the main sources of indoor CO. There have been related studies designed to start CO monitoring when the water heater is used. When the alert setting is activated, the alarm message is sent to the mobile phone via Wi-Fi [32]. CO sensors are often included in the planning of health or safety monitoring systems. Unfortunately, the CO Forecasting Model is usually not the design focus of the aforementioned systems. Most systems still use a single preset warning value as a management benchmark for CO monitoring applications.

3 Method

3.1 Case Investigation Plan

Commonly used water heaters in Taiwanese bathrooms are powered by electric and gas, while CO poisoning events are mainly caused by gas water heaters because of incomplete gas combustion. Gas water heaters that are used in townhouses, apartments, or community blocks are mostly installed at the working balcony to maintain good ventilation. However, because of the limitations of high housing prices and insufficient space, the public often installs closed windows at the working balcony to hang their clothes to dry. This often greatly decreases causes the working balcony ventilation. Rain avoidance, the northeast monsoon during the winter, or privacy problems often cause people to close illegal windows in their working balcony, forming an enclosed space. This causes a health and safety risk because of the inability for CO produced from gas water heaters to escape.

In this study, residents who use gas water heaters were the study subjects and the gas water heater was assumed to be the source of CO pollution. During the study, handheld CO analyzers (GCO-2008) were used for on-site detection and recording to examine gas water heaters during use (in combination with hot water usage during bathing) to examine changes in indoor CO concentrations. In this study, we examined 10 cases, and the working balcony where the water heater was installed was taken to be the pollution source and measurement point. In addition to dynamic CO concentration changes, the content recorded during testing included whether illegal windows were installed, clothes were hung, junk was present, and mandatory exhaust equipment was installed at the working balcony.

The total measurement duration for each case was 30 minutes. At the start, the environmental background value was measured. Following this, the user was asked to start using the gas water heater. Usually, the measurement duration when the water heater is used is approximately 10-20 minutes. After the user has stopped using the water heater, the device will continuously measure and record until 30 minutes. To avoid the CO produced during measurement from affecting the health and safety of the tester and others, all doors and windows connecting the working balcony to the interior of the house are completely closed during measurement to avoid CO escape into the house and endangering health or safety.

3.2 Selection and Calibration of Sensors

In this study, electrochemical sensors were used. In the sensor, electrolytes and the target gas undergo a redox reaction, producing a microcurrent. Typically, the microcurrent is positively correlated with the concentration of the target gas, and the current flows through the working electrode (WE) to an external circuit, thereby producing an output signal. During this experiment, the model of the electrochemical CO sensor was a TGS5042-A00 (See Figure 1). The TGS5042-A00 has greater selectivity and sensitivity, easier calibration, and a longer lifespan compared to those of other sensors.

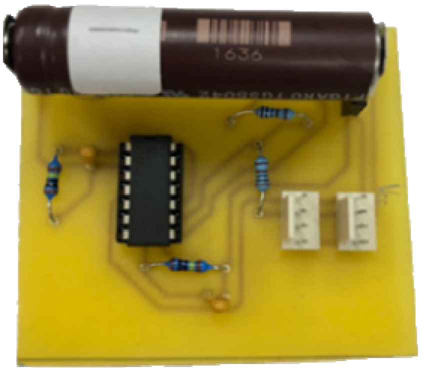

Figure 1. Electrochemical CO sensors

The sensor produces a current signal as output and its detection range is 0-10,000 ppm. Its precision is 1 ppm and its sensitivity is 1.2-2.4 nA/ppm. In addition, the greater the measurement range, the lower the precision. The output current (I_{out}) of this sensor flows through a fixed resistance of 1MΩ(R), which converts current to voltage (V) by Ohm's law. The voltage is converted into air CO concentration and the conversion formula is shown in Equation 1 as follows:

$$V = I_{out} \times R = I_{out} \times 10^{6} \qquad \textbf{(1)}$$

Regarding sensor calibration, the sensor tends to have a problem of component heterogeneity, zero shift in a clean air environment, and errors when different sensors are used to measure the same stable concentration. However, measurement of a stable concentration will result in values having the same concentration. This causes the concentration errors of different sensors to be different and this cannot be corrected by simply deducting the error.

In this study, calibration experiments were conducted first before every experiment and the calibration equation was used for sensor calibration. Figure 2 shows the self-designed calibration apparatus. The calibration was to inject a small amount of CO gas through a syringe (Figure 2(a)) into a self-made 30×30×30 cm closed acrylic box; the handheld CO analyzer (Figure 2(b)) was used as a basis for calibration. Finally, the electrochemical CO sensor module (Figure 2(c)) was used to collect data and send it to the computer. The calibration formula was used to calibrate the measurement data from the sensor. The sensor module in Figure 2(c) includes the electrochemical sensor, analog/digital converter, and data acquisition system.

The principle of calibration is to assume that Sensor $A_{original}$ is the raw data, Sensor A $_{calibrated}$ is the post-calibration data, and γ ppm concentration is the calibrated concentration. Assume that the mean zero-point concentration of the sensor falls in α ppm and is not 0 ppm, and β ppm is the difference between the final and starting concentration. Equation 2 shows the calibration formula and Figure 3 shows the calibration results for three different concentrations (150/180/200 ppm). The mean error percentage of the CO sensor at a calibration concentration of 150 ppm can decrease from 14.6 to 19.3% before calibration and stabilizes at 0.6-4%. At a calibration concentration of 180 ppm, the mean error percentage can decrease from 17.2 to 23.3% before calibration and stabilizes at 2.2-3.8%. At a calibration concentration of 200 ppm, the mean error percentage can decrease from 18 to 21% before calibration and stabilizes at 2-4%.

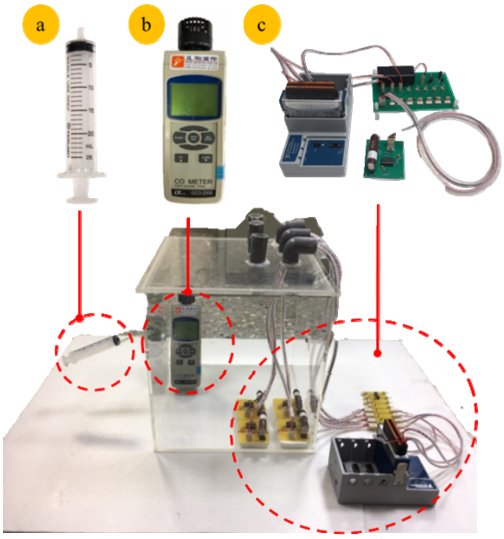

Figure 2. Calibration apparatus

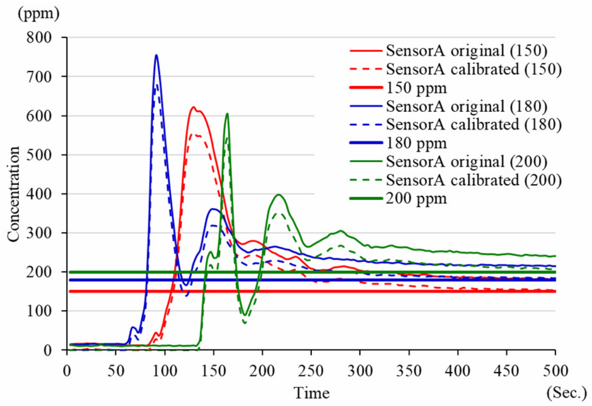

Figure 3. 150/180/200 ppm calibration results

$$Sensor\ A_{calibrated} = (Sensor\ A_{original} \times \alpha) \times \frac{\gamma}{\beta} \qquad \textbf{(2)}$$

1000 1000 1000 1000
0 0 0 0

3.3 Experimental Design of Model House

If an actual house is used to measure high-concentration CO escape, it will face issues of safety, cost, and cooperation willingness in subjects and thus is not feasible. Therefore, in this study, a common house model with an indoor net area of 100 m^2 was used as a simulation subject and a 1:10 acrylic model house was made. The model included bedrooms 1-3, a living room, a kitchen, two bathrooms, and a front and rear balcony (working balcony). In the working balcony, illegal windows were simulated to form an enclosed space. The working balcony was planned to be adjacent to the window of bedroom 1 (W1) and the door of the kitchen (D1). There is a door between bedroom 1 and the indoor passageway (D2). Both D1 and D2 can be closed and opened.

The working balcony is the main region for simulating a CO pollution source in this study and the CO pressure cylinder placed beside the model house provided CO (Figure 4(a)). The gas pressure regulator valve of the CO pressure cylinder was used to set a fixed pressure (Figure 4(b)) and the throttle valve was used to set the flow rate (Figure 4(c)). Finally, the gas has been split into multiple pipes (Figure 4(d)). CO from the cylinder that flows outside the house was pumped to the roof through an exhaust fan to ensure the safety of the experimental staff (Figure 4(e)). The CO tube at the end was connected to the working balcony in the acrylic model house to deliver trace amounts of CO into the closed working balcony (Figure 4(f)). The CO sensor was installed at the working balcony. The values measured by the sensor are transmitted through wires to the analog/digital converter and data acquisition system receiver module (Figure 4(g)). The aforementioned receiver module was placed beside the acrylic house and a USB cable was used for wired transmission of signals to a laptop (Figure 4(h)).

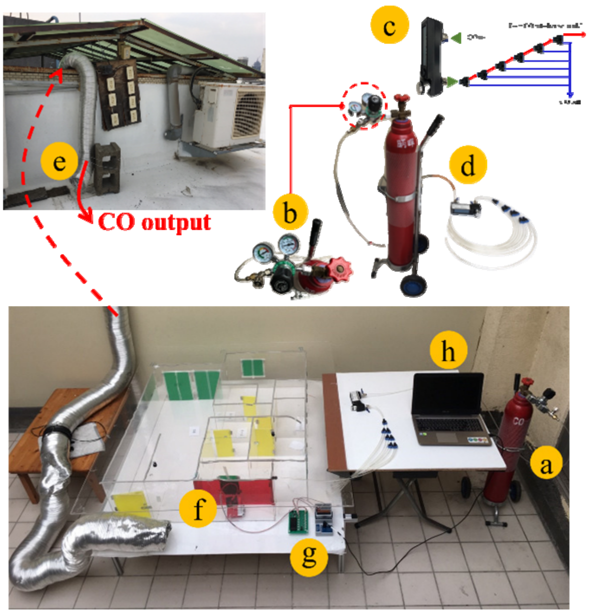

Figure 4. Model house experimental setup

3.4 Experimental Scenario and Weighing

The hazard simulation scenario is an enclosed space (working balcony) in which incompletion combustion in the gas water heater produces CO. A simulation of three doors and window open/closure scenarios was conducted, in which bedroom 1 is connected to the working balcony through a window (W1) or connected to the indoor passageway through a door (D2), and the kitchen is connected to the working balcony through a door (D1) (Table 1). We quantified and analyzed the dynamic CO concentrations obtained by the CO sensors under scenarios 1 to 3. Theoretically within a specific duration, when W1 and D1 were closed, the cumulative CO concentration or concentration increase rate measured in the working balcony should be the greatest (Scenario 1). In contrast, when WI, D1, and D2 are opened, the cumulative CO concentration or concentration increase rate measured in the working balcony should be the lowest (Scenario 3).

Table 1. Model house experimental scenarios

	W1	D1	D2
Scenario 1	Close	Close	Close
Scenario 2	Open	Close	Close
Scenario 3	Open	Open	Open

Regarding measurement weighing, many studies often address the problem of numerical fluctuations through a weighted moving average. An example is a study that used this method to calculate the outdoor temperature to correctly predict building heat loss [33]. In this study, the oxidation reaction between the gas and the sensor was used to obtain the air CO concentration. In addition to the effects of high selectivity of the sensor for gases in the air on measurement accuracy, the high air flow rate also affects the sensor reaction speed. Similarly, to avoid excessively high fluctuations in the measurement values, which will affect the accuracy and stability of the measurement model, the weighted moving average method was used to filter numerical perturbations in the time series. These were shifted according to the sequence of the data points such that irregular data are smoother. Equation 3 shows the CO value formula in the weighted moving average, of which N_t is the weighted average and Y_t is the CO concentration, as follows:

$$N_t = 0.5Y_{t-1} + 0.25Y_{t-2} + 0.15Y_{t-3} + 0.1Y_{t-4} \qquad \textbf{(3)}$$

During measurement by the CO sensor, the conversion formula in Equation 3 was used and every measurement value was presented in the form of a weighted moving average. Following this, the weighted values were used for analysis and construction of the prediction model.

4 Experimental Results and Performance Evaluation

4.1 Case Analysis Results

We examined a total of 10 cases in this study. The residence type ranged from an apartment block to a townhouse. As the precision of the device used in this study was 1 ppm and the lowest concentration was 0, some results were shown as 0 if they were less than 1 ppm. During the case survey, external material was used for comparison. The source of these external materials was the atmospheric CO concentration in nearby monitoring stations that are published on the website of the Central Weather Bureau of the Republic of China; the measurement precision was 0.01 ppm.

The working balcony is the main investigation and measurement site, as the gas water heater is there, and incomplete combustion will produce high CO concentrations. In addition, there is a high risk of CO poisoning if the ventilation is poor or when the area is enclosed. The working balcony design and status and usage conditions of the gas water heater in the 10 cases were all different. In some cases, a mandatory exhaust pipe (Figure 5(a)) was installed in the gas water heater and the installation method was correct and effective. Closed windows were installed in the working balcony in some cases, and the mandatory exhaust pipe was not installed in the gas water heaters (Figure 5(b)). Although some working balconies did not contain the mandatory exhaust pipe, ventilation was good (Figure 5(c)).

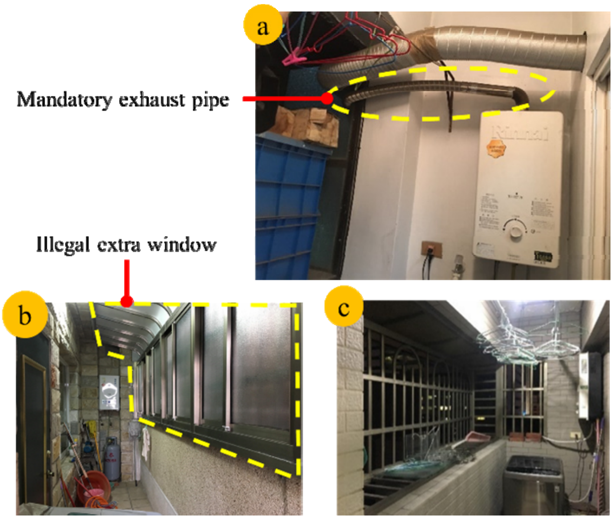

Figure 5. Working balcony risk status

Some cases have obvious safety problems while others have latent health safety concerns (CO concentration >9 ppm). Figure 6 shows the CO concentration results of the 10 cases. We selected the more distinctive Cases 3, 5, and 6 for further explanation. Case 3 had good ventilation and although the CO concentration was not high, it was still higher than the health standard (9 ppm). Case 5 was an enclosed place and the measurement of Case 5-1 was a state in which the windows were closed while the measurement of Case 5-2 was a state in which the windows were opened. Using the bathing time period of Case 5-1 shown in Figure 6 as an example, the CO concentration instantaneously increased during the 10th min (an increase of 130 ppm within 1 min). Although Case 6-1 (townhouse 3F) had good ventilation the CO concentration was extremely high (greater than 450 ppm). Although Case 6-2 (townhouse 2F) did have the mandatory installed exhaust pipe, because of insufficient pipe length, the CO concentration was higher than the health standard though it was not as high (<50 ppm).

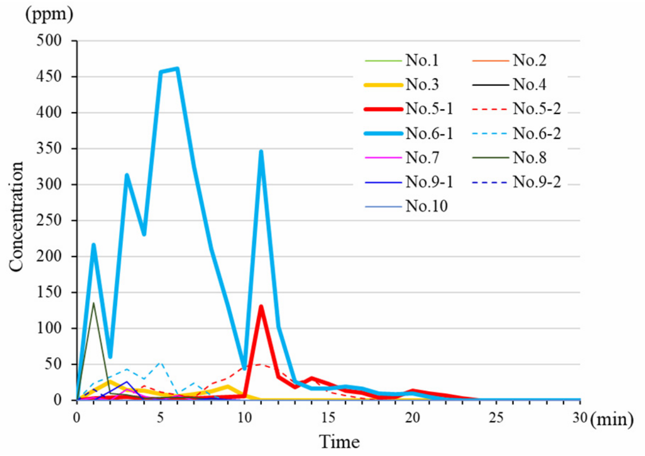

Figure 6. CO measurement data of 10 cases

In Case 3, the owner installed the gas water heater at the balcony and did not install the mandatory exhaust pipe. The balcony is an open balcony and is near the kitchen (the kitchen door was closed during measurement) and no windows were installed. The ventilation was good. The measurement period was 21:40-22:10 on June 4, 2019. On that day, the outdoor CO concentration measured by the Taichung meteorological station at 21:00 was 0.4 ppm. Figure 7 shows the changes in CO concentration after 30 minutes of measurement. The usage duration of the gas water heater was approximately 10 minutes. During the first 10 minutes, the maximum CO concentration in the balcony was 20 ppm. After the water heater was turned off, the balcony CO concentration immediately decreased to 0 ppm. From this case, we can see that even if the working balcony is completely ventilated, the use of the water heater will still produce CO. Although this concentration does not present any safety issues, there is still a risk of a health hazard. During measurement, the CO concentration was higher than the health standard of the Indoor Air Quality Act of Taiwan. When the wind blows indoors or if clothes are hung and gas exhaust is blocked, there is an extremely high probability that CO will enter indoors and affect the IAQ of the home.

In Case 5, the balcony is a closed balcony with windows installed and is near the kitchen. The mandatory exhaust pipe was not installed for the water heater and clothes were hung on the balcony. The measurement period was 21:00-21:30 on June 9, 2019. On that day, the outdoor CO concentration measured by the Taichung meteorological station at 21:00 was 0.39 ppm. There were two 30-min measurements at the

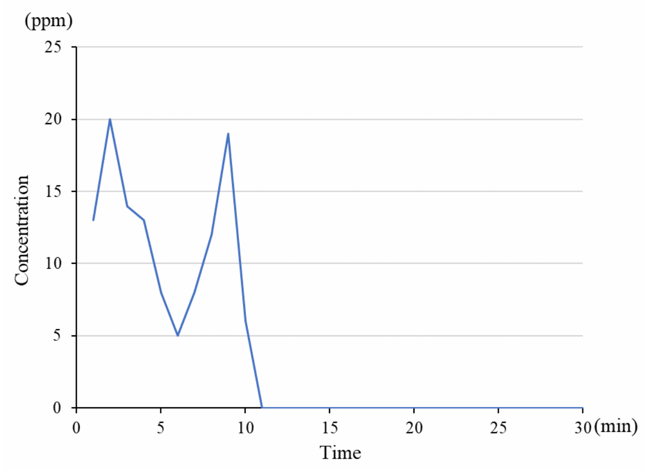

Figure 7. Case 3 CO concentration changes

same site for Case 5. The first was when it was sealed and windows were not opened (Case 5-1 data), and the second was when the windows were opened and ventilated (Case 5-2 data). Figure 8 shows all obtained concentration curves. During the first measurement (Case 5-1), the windows of the working balcony were closed, and the water heater operated until the 12th min. The CO concentration instantly increased to 130 ppm. At this point in time, the tester had mild dizziness and other discomforts. Because of safety considerations, the windows were opened at the 13th min and the CO concentration in the balcony decreased to 0 ppm at the 24th min. In the second measurement (Case 5-2), the windows of the working balcony were completely opened, and the water heater was turned on until the 16th min. It was found that although the CO concentration was significantly lower than the first measurement during this period, it was still greater than 50 ppm.

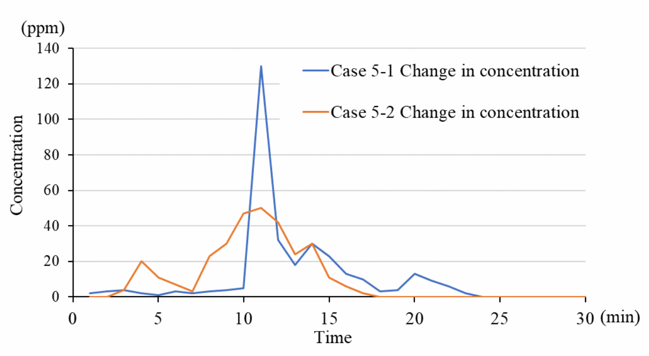

Figure 8. Case 5 CO concentration changes

In Case 6, the subject was the entire townhouse, and there were two measurement locations: 2F and 3F. The water heater in Case 6-1 (townhouse 3F) was extremely old and the mandatory exhaust pipe was not installed. The water heater in Case 6-2 (townhouse 2F) was new and the mandatory exhaust pipe was installed. The measurement period for Case 6-1 was 09:42-10:12 and that for Case 6-2 was 11:00-11:30 on June 5, 2019. On that day, the outdoor CO concentration measured by the Taichung meteorological station at 09:00 was 0.38 ppm. Figure 9 shows the CO concentration changes in the two measurements. Although the working balcony in Case 6-1 was completely ventilated without obstruction and not used for hanging clothes, the water heater was extremely old and unstable. The usage duration of the gas water heater in Case 6-1 was approximately 10 minutes. During the 3rd min, the CO concentration in the balcony was 300 ppm and it exceeded 450 ppm during the 6th min. After the water heater was turned off, the balcony CO concentration decreases to 0 ppm after 12 minutes. The water heater and ventilation statuses of Case 6-2 were both good. However, because of insufficient extension of the exhaust pipe and the effects of wind blowing from the outside to the inside, although the CO concentration was less than 50 ppm, it was still higher than the health standard.

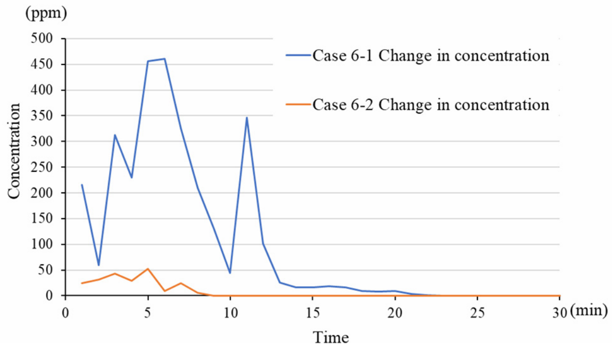

Figure 9. Case 6 CO concentration changes

From an analysis of the aforementioned cases, we can see that the logic for installing CO sensors in smart homes at the moment is to design for placement on the kitchen ceiling. When this sensor detects pollution from the working balcony, the source at the balcony may have accumulated for a period of time and the concentration is high, resulting in insufficient immediacy for safety and health warnings. In addition, even if the mandatory exhaust pipe was installed for the gas water heater and ventilation at the working balcony was good, wind direction or an old gas water heater may result in a high CO concentration, resulting in a poisoning hazard or health effects. Therefore, selection of a suitable site for installing the CO sensor or constructing a suitable warning model is necessary for home safety and health management.

4.2 Construction of the CO Multi-Forecasting Model

The warning model designed in this study is termed the CO Multi-Forecasting Model. It is hoped that it can become an AIoT application based on semi-supervised learning (SSL) and warning models for the two management goals of health and safety. The construction benchmarks for CMFM originate from different diffusion paths and spaces. The experiment results of three scenarios were used to analyze the rate of change (slope) of the dynamic CO concentrations that were measured. An initial regression analysis was used to obtain the preliminary model prototype before introduction into AI learning. The total measurement duration for each group of scenario experiments was 500 s and values were automatically recorded every 5 s. Figure 10 shows the measurement values and regression formula for Scenarios 1-3.

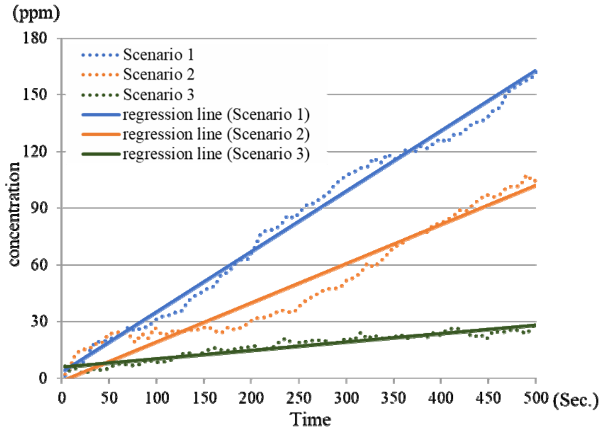

Figure 10. Slope of scenarios 1-3

The window and door setting for Scenario 1 was as follows: W1(closed)+D1(closed)+D2(closed), which is generally a state in which all windows and doors were closed. Under this scenario, the pollutant will, in theory accumulate at the working balcony. Therefore, the concentration increase rate detected by the CO sensor should be the fastest (highest slope). When the experimental results from Scenario 1 were used for regression analysis, CMFM Model 1 (R^2=0.992) could be obtained. For details, please see Model 1 in Equation 4 and Figure 10.

$$\text{CMFM Model 1} = 0.3193x+3.002 \tag{4}$$

The window and door setting for Scenario 2 was as follows: W1(open)+D1(closed)+D2(closed). Under this scenario, the pollutant will in theory gradually spread from the working balcony to bedroom 1. Therefore, the concentration increase rate detected by the CO sensor should be slower than the result in Scenario 1. When the experimental results from Scenario 1 were used for regression analysis, CMFM Model 2 (R^2=0.957) could be obtained. For details, please see Model 2 in Equation 5 and Figure 10.

$$\text{CMFM Model 2} = 0.2074x - 1.5928 \tag{5}$$

The window and door setting for Scenario 3 was as follows: W1(open)+D1(open)+D2(open), which is generally a state in which all windows and doors were opened. Under this scenario, in addition to the spread of the pollutant at the working balcony to bedroom 1, the pollutant will spread from the kitchen to the living room and the passageway. Therefore, the concentration increase rate detected by the CO sensor should be the slowest among the three scenarios (lowest slope). When the experiment results from Scenario 3 were used for regression analysis, CMFM Model 3(R^2=0.909) could be obtained. For details, please see Model 3 in Equation 6 and Figure 10.

$$\text{CMFM Model 3} = 0.0449x + 5.6473 \tag{6}$$

Common indoor CO poisoning events seen in Taiwan tend to be nearer to conditions under Scenario 2 or Scenario 3. The effects of CO on the human body range from health effects and discomfort to immediate death. Human health will be affected when CO exceeds 9 ppm but the warning threshold for a commercially available CO alarm is set to 30 ppm. When the human body inhales 200 ppm of CO, mild headaches will occur within 2-3 h. When the human body inhales 1600 ppm of CO, headaches and dizziness will occur within 20 minutes and death will occur within 2 h. The CMFM proposed by this study is different from the fixed alarm value of commercially available CO alarms. The CMFM warning determination has four management thresholds: Health level (9 ppm), Alarm level (30 ppm), Action level (200 ppm), and Urgent level (1600 ppm). Table 2 shows the time values corresponding to the four management thresholds in the CMFM under the 3 scenarios.

Table 2. CMFM model alarm time

CMFM Alarm Level	Model 1 Alarm time (sec)	Model 2 Alarm time (sec)	Model 3 Alarm time (sec)
Health 9 ppm	18	51	75
Alarm 30 ppm	84	152	542
Action 200 ppm	616	972	4328
Urgent 1600 ppm	5001	7722	35508

Using CMFM Model 2 as an example, the alarm level set in a traditional commercially available sensor is 30 ppm. In this study, when the health level was used as the prediction standard (9 ppm) for Model 2 Alarm time, 2.9 times the alarm time, 19 times the Action level alarm time, and 151 times the Urgent level alarm time than traditional commercially available sensors can be obtained. When CMFM Model 3 was used as an example, 7.2 times the alarm time could be obtained for Model 3 Alarm time in this study. In short, the CMFM in this study can in advance obtain 3-7 times the alarm time compared to commercially fixed (30 ppm) alarms.

4.3 CMFM Management Interface

The CMFM Management Interface primarily presents content such as time, sensor work status, digital and visual presentation of CO concentration and slope, concentration values, and alarm signals of spaces that are mainly affected (working balcony, bedroom, and kitchen). The alarm lights were divided into four colors representing grades: green (health level, 9 ppm), yellow (alarm level, 30 ppm), orange (action level, 200 ppm), and red (urgent level, 1600 rpm) to facilitate observation using the monitor (Figure 11). In the visual display screen, there are two linear displays: CO concentration and slope. The boundaries of the aforementioned four hazard alarms are shown for the concentration value to enable the monitor to see the concentration during monitoring.

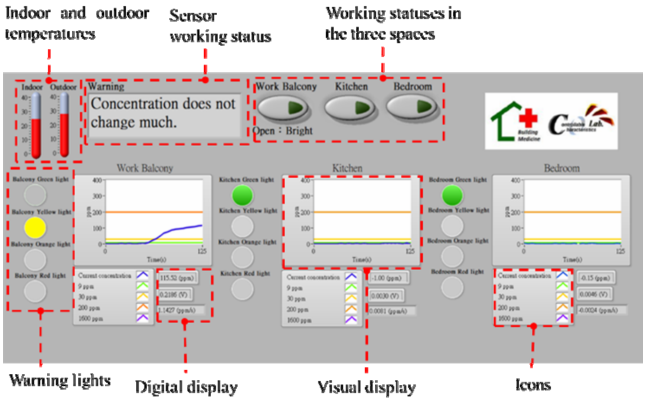

Figure 11. CMFM management interface

5 Discussion

5.1 Sensor is the Key for Indoor CO Crisis Management

There are multiple causes of home CO poisoning such as device factors (old gas water heaters and non-installation of mandatory exhaust pipes), human factors (illegal windows that open outwards and hanging of clothes at the working balcony that affect ventilation), and natural factors (natural wind concentrating pollutants) that may cause the working balcony to produce excessively high CO concentrations, thereby increasing home health and safety risks.

From the investigation of 10 cases in this study, we found that even when new gas water heaters are installed, the mandatory exhaust pipes are installed, and there is no ventilation problem at the working balcony, external natural wind may still blow the pollutant indoors or retain pollutants near the working balcony, greatly increasing the CO poisoning risk. The warning function of the sensor can be considered as the last line of defence in indoor CO risk management and it is extremely important in-home safety and healthy environment management.

5.2 Misunderstanding in CO Sensor Setting

The CO sensor which the current design located on the kitchen ceiling is not an ideal choice. The CO sensor warning effectiveness, time, and distance from the pollution source show a positive correlation. Theoretically, the closer the sensor is to the pollution source, the greater the effectiveness. The gas stove used for cooking is viewed as a major pollution source in the original plan. However, the cause of death resulting from CO poisoning is always because of insufficient combustion in the gas water heater at the working balcony that produces large amounts of CO. A site near the pollution source (working balcony) should be the primary consideration.

5.3 CMFM Solution in AIoT Applications

Because of rapid improvement in and large-scale use of technology, the introduction costs for smart homes is decreasing year-by-year. Similarly, the number of sensors installed is also increasing because of a cost reduction. Installation of more sensors will add to collection of big data and help promote the IoT in smart homes or cities. Appropriate installation of CO sensors will aid in the accumulation and observation of dynamic changes in different environments or scenarios and a database of CO concentration variation slopes obtained will help to increase the breadth and depth of the CMFM.

6 Conclusion and Suggestion

At present, the layout of the CO sensor is considered in a smart home. Although this helps in simple and conservative safety alarms, it is insufficient in health hazard management or even timely and early warning. In this study, CO sensor design, 1/10 experimental model house construction, and analysis of the simulated scenario values of the three hazard scenarios were used to preliminarily construct the CMFM that can predict the CO poisoning hazard. We designed a human–machine interface that can be used for management. In warning decision making, the CMFM also simultaneously considers the two management goals of health and status to design four management thresholds for home CO concentrations as follows: Health level, Alarm level, Action level, and Urgent level. By using the safety level as an alarm example, the CMFM of this study can bring shorten the alarm time by 3-7 times compared to commercially available CO alarms.

Because of limitations in the equipment budget and experimental duration, we could only use the throttle valve and the split pipe to reduce CO levels to a reasonable trace experimental value. In this study, incomplete combustion in the gas water heater was considered to be the sole pollution source and mainly originated in the working balcony. However, in addition to water heaters, a gas stove in the kitchen, indoor coal burning for suicide, indoor charcoal hotpots, smoking, or placing gas water heaters indoors will cause non-natural CO to be present indoors. We recommend that future researchers should consider including the aforementioned pollution sources for investigation if permitted based on funding, time, and manpower.

The CMFM created in this study is a linear prediction model. However, the prediction trends of many real-life practical scenarios are not completely linear. We recommend that AIoT be used for deep learning regarding different family usage scenarios in the future and a diverse and rational non-linear CMFM can be attempted to obtain a more comprehensive, complete, and smarter hazard identification and warning model. Although the design logic of this study used a large number of sensors, simulation of different pollutant concentrations, and planning of different hazard scenarios for big data collection and learning, these require considerable use of manpower, funds, and time; it is not an economical study method. In addition, even if AI is used for training, the cost of using actual material to train the model is very expensive in both academia and industry and most require manual labeling and selection. In addition, some scenarios lack data or are not easily obtained, making the model training process extremely difficult. It is recommended that future researchers attempt to use the mutual learning mechanism between generators and discriminators in Generative Adversarial Networks, which may solve this problem. The smart home and smart city are developmental goals that various countries have been striving to achieve during recent years. The presence of large numbers of sensors and transmission speed will be solved by employing 5G technology. In the future, when AI is used for analysis of health monitoring and hazard management countermeasures in smart homes, the public safety database developed by governments can be used for mutual data exchange and big data analysis and integration of AIoT technology to establish a CO concentration change alarm logic for individual homes or spaces. This can be used for real-time monitoring or determination and combined with information transmission in a human–machine interface. This will be used to notify of abnormal linear and non-linear trend changes through sound, light, images, and mobile phone push notifications or third-party notifications in the form of real-time multiple alarms. At the same time, information can be provided to relevant government agencies such that they can fully use this important public safety information for safety management in a smart city.

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