Optimized Control of Indoor Environmental Health - Example of the Fu-An Memorial Building

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ABSTRACT

This study proposes the establishment of an environmental health information management platform providing residential users a comfortable, healthy indoor environment. Taking the Fu-An Memorial Building, as an example, the design of the control logic algorithm ensures that the environmental health information management platform can simultaneously: (1) provide a healthy indoor environment and (2) realize optimized control mechanisms and methods minimizing the energy consumption of the building's environmental control equipment. Because of this, the Fu-An Memorial Building uses (1) PMV thermal comfort sensors, (2) energy-conserving environmental controls, and (3) natural ventilation to regulate the building's interior microclimate, realizing an energy-saving, environmentally-friendly, smart building. The study and building construction work revealed that the next stage should include: (1) development of an expert system to control the health environment, (2) establishment of an information processor learning mechanism, and (3) development of adaptive logic control technology.

Keywords: optimized control, building environmental control system.
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1 MOTIVATION AND GOALS

This study proposes the establishment of an environmental health information management platform providing optimized control mechanisms and methods for the heating and air conditioning environment. Motivated by users' increasing demand for a healthy environment, sustainability, and energy conservation, the development of suitable logic algorithms has become an important element of the design of contemporary smart residential spaces. Because of this, this study proposes the development of an environmental health information management platform based on the results of a review of the literature and the Fu-An Memorial Building case; this platform can be used to analyze and determine the necessity and feasibility of optimized control of the health environment, and guide future development.

2 LITERATURE REVIEW

This study performed a review of literature on (1) optimized control theory and (2) building environmental control systems in order to gather information on optimized control of the health environment, and proposed optimized control mechanisms and methods for the thermal air-conditioning health environment.

2.1 Optimized control theory

Optimized control refers to the most appropriate solution ensuring a healthy environment under the constraints of the architectural environment. Generally speaking, there are two types of optimized control, namely (1) mathematical equations and (2) logic control. Because users' activities in their living environment are typically sporadic, dynamic, discrete, and nonlinear, they cannot easily be expressed using mathematical equations exclusively. This study consequently advocates the use of logic control to drive the responses and actions of equipment and architectural elements under the constraints of the architectural environment in order to establish and maintain an optimal environment [4].

In ordinary optimized control problems, the control system must ensure that the performance of the plant satisfies or approaches pre-set indicators while complying with managers' pre-set constraints. In the field of automatic control, optimized control must possess three key elements: (1) system performance indicators, (2) constraints, and (3) optimized control mechanisms and methods [2, 3]. Chen (2002) suggests that optimized design requires the establishment of an appropriate physical model for an engineering design problem, the construction of mathematical equations on the basis of that model, and use of the model to derive an optimal design. However, if the actual situation changes, the state of the physical model must be regularly inspected to determine whether it is consistent with predictions and the design must be modified if it is not consistent [6].

This study consequently proposes the adoption of logic control. Logic control employing a rule-based expert system is termed an optimized control system. An expert system is a knowledge based program that can be used to resolve problems in a certain area, and which provides answers similar to those given by an expert. The expression of knowledge in the system adopted in this project employs production representation (or rule representation), which is currently the most widely-used knowledge representation method in expert systems. Many well-known expert systems employ this type of representation method, including the MYCIN system and PROSPECTOR system. (Chang, 1993) According to the definitions of Weiss and Kulikowski (1984), an expert system is a computer program developed to mimic the thinking and inferences of experts, and is used to resolve complex problems that can only be solved by experts. According to the definition of Feigenhaum (1985), an expert system is an intelligent computer program employing knowledge and inferences to resolve highly specialized knowledge-related problems. [5]

According to Menzies (1996)[12], there are three types of logical reasoning methods: (1) deduction, (2) induction, and (3) abduction. Through the use of a given premise, conclusions, and rules, we can derive conclusions from the premise. Here, deductive reasoning asserts that "conclusions can invariably be derived from known facts referred to as the premise." In deductive reasoning, the conclusions are certainly true if the premise is true. [16]

The analytical operating cycle employed in logic control includes: (1) matching, (2) elimination of conflicts, and (3) operating processes. This cycle continues until the problem is solved, and the process can be used to find optimal control solutions. The logic control mechanism for the Fu-An Memorial Building is described in detail in section 3.4.

(1) **Matching**: In the solution process, the information processor bears responsibility for comparing rule conditions with the content of its database; this is known as matching.
(2) **Elimination of conflicts**: Because more than one rule may need to be matched with the database during the problem-solving process, the logic control must employ an appropriate control strategy able to select which rule is activated. This process is known as the elimination of conflicts. A truth table may be employed during this process for selection and debugging, and can be used to determine the correctness of the deductive reasoning.
(3) **Operating processes**: The information processor decides which rules can currently be matched with the database in the current state; these are known as enabled rules. The logic control executes the enabled rules, and changes the database on the basis of the actions of the enabled rules. Changing the database may also trigger new rules, which will take the problem-solving process to the next state. This process continues until the problem has finally been solved.

2.2 Building environmental control systems

According to Chen (2011), building environmental control systems apply information processing technology to achieve optimized management of environmental control. [7] The system framework in this study includes the (1) information source, (2) environmental health information management platform, and (3) the plant. This system framework is as shown in Fig. 1, and is explained below.

(1) **Information source**: The information source refers to the origin of information in the building environmental control system's external environment. Information sources include physical environmental factors and user needs. After the building control system collects external information, including physical environmental factors and user needs, this information is transmitted to the environmental health information management platform for subsequent processing.
(2) **Environmental health information management platform**: The environmental health information management platform is the key element in optimized management of environmental health. In order to respond to changes in the external environment, the environmental health information management platform must fulfill its goal of optimally managing equipment and dynamically regulating environmental factors so as to meet home users' need for comfort. The environmental health information management platform includes inputs, information processor, and outputs; the system's constituent elements are described in detail in section 3.3.
(3) **Plant**: The plant refers to the building environmental control system's action and effect (actuation control and communication activities) unit, and includes actuators and information monitors. When the plant receives a command from the environmental health information management platform, it implements control of the actuator and information monitor status.

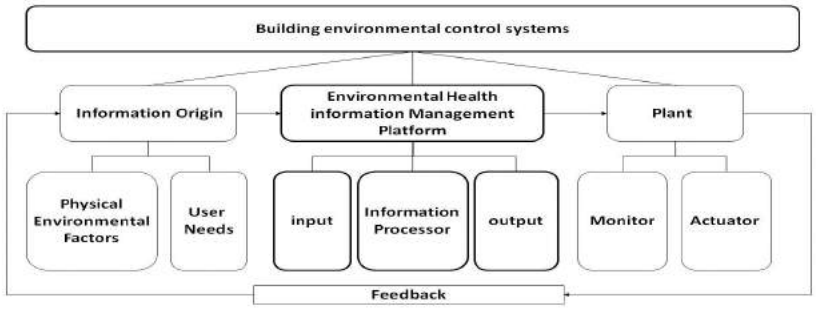

Fig. 1: Block diagram of the Fu-An Memorial Building environmental control system.

3 EXAMPLE OF THE FU-AN MEMORIAL BUILDING

Based on the foregoing research, the environmental health information management platform installed in the Fu-An Memorial Building in this study relies on the control logic algorithm design to provide optimal control mechanisms ensuring the quality of the indoor health environment and minimizing energy consumption by environmental control equipment.

3.1 Overview of site conditions and design concept

The Fu-An Memorial Building is an 11-story office building located in Taipei. Its geographical location is at E121° 33', N25° 2' . The environment around the site primarily consists of office buildings. The building faces north and has its back to the south (see Fig. 2). Fig. 3 provides a schematic diagram of the appearance of the Fu-An Memorial Building.

Fig. 2: Current status of the environment around the Fu-An Memorial Building.

Fig. 3: Schematic diagram of the appearance of the Fu-An Memorial Building.

3.2 Compliance with passive design principles

In order to achieve environmental sustainability, the Fu-An Memorial Building complies with passive architectural design principles. The use of passive design principles to improve environmental health and building energy conservation hinges primarily on the natural meteorological conditions outside. The design of this building seeks to ensure that openings in the building facilitating natural ventilation can significantly improve indoor thermal comfort conditions without the expenditure of energy, promoting human health. The Fu-An Memorial Building is located in the subtropical zone, and average climate data for Taipei city is shown in Table 1. The east wind prevails year-round, the average annual temperature is 22.8°C, and the average annual relative humidity is 77.1%. The climate can be considered hot and humid. The Fu-An Memorial Building possesses excellent natural ventilation conditions. The fact that the public stairwell is located on the east side of the building (Fig. 4: standard floor plan of Fu-An Memorial Building) facilitates the use of natural ventilation to regulate the thermal air conditioning health environment.

The environmental health information management platform uses natural convection in a ventilation tower comprising the public stairwell on the 8th-11th floors of the Fu-An Memorial Building to vent hot indoor air through air shutters at the top of the stairwell (Fig. 5: schematic diagram of ventilation tower; Fig. 6: photograph of actual electric air shutter on 11th floor; Fig. 7: photograph of actual central axis window on 8th floor).

Items	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual average
Temperature (℃)	16.0	16.0	18.2	21.7	24.9	27.6	29.4	29.1	27.2	24.2	21.2	17.7	22.8
R H(%)	79.1	81.4	81.2	78.2	77.5	77.0	73.5	74.6	75.9	75.5	75.7	75.4	77.1
Rainfall(mm)	83.2	170.3	180.4	177.8	234.5	325.9	245.1	322.1	360.5	148.9	83.1	73.3	-
Ave number of rainy days (Ó 0.1 mm)	14.1	14.6	15.5	14.9	14.8	15.5	12.3	14.0	13.8	11.9	12.4	11.7	-
Wind direction	E	E	E	E	SSE	SSE	SES	E	E	E	E	E	E
Ave wind speed(m/s)	2.9	2.9	2.7	2.7	2.6	2.4	2.3	2.5	3.0	3.6	3.5	3.1	-
Max wind speed (m/s)	9.6	10.2	11.4	12.0	10.5	10.8	17.1	19.4	16.4	13.5	10.5	10.3	12.7

Tab. 1: Average climate data for Taipei (1981-2010)
Source: Central Weather Bureau (R.O.C), http://www.cwb.gov.tw/V7/index_home.htm

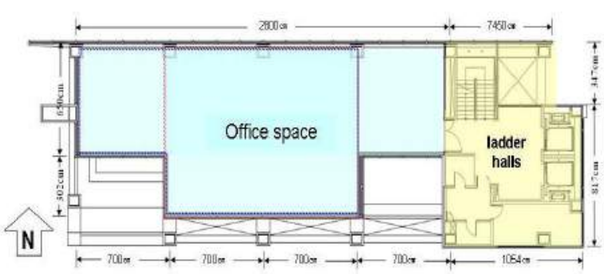

Fig. 4: Standard floor plan of Fu-An Memorial Building.

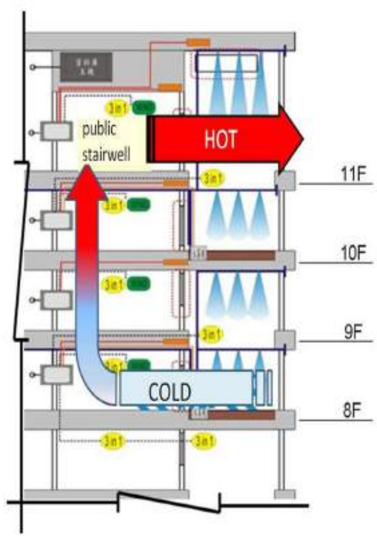

Fig. 5: Schematic diagram of ventilation tower.

Fig. 6: Photograph of electric air shutter on 11th floor.

Fig. 7: Photograph of central axis window on 8th floor.

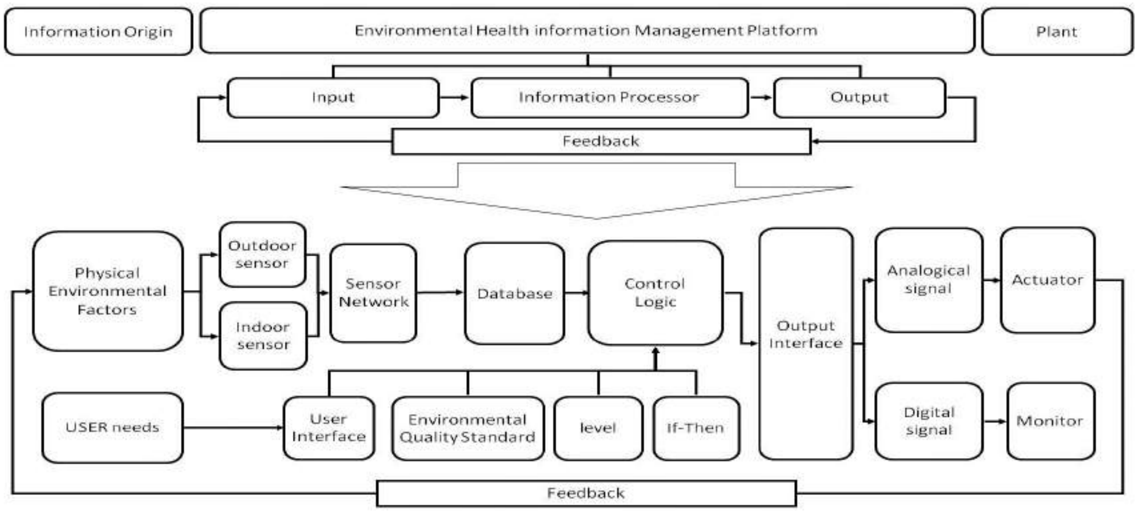

Fig. 8: Structure of environmental health information management platform system in the Fu-An Memorial Building.

3.3 Environmental health information management platform system structure

An environmental health information management platform has been installed in the Fu-An Memorial Building to ensure the coordinated action of control equipment and architectural elements, enabling the maintenance of a healthy environment and optimal equipment energy conservation. The structure of the environmental health information management platform includes inputs, an information processor, and outputs. Fig. 6 and Table 2 provide further information concerning the environmental health information management platform in the Fu-An Memorial Building.

(1) **Inputs**: Inputs include the user interface, indoor sensors, and outdoor sensors. Users can employ the user interface to manually control equipment in the building. The indoor sensors collect information including the indoor temperature, humidity, air speed, carbon dioxide concentration, and power consumption. The outdoor sensors collect information including outdoor temperature, humidity, wind speed, and wind direction. The collected data is transmitted to the information processor.

(2) **Information processor**: The information processor monitors information on the indoor health environment and the control of driver equipment in order to ensure optimized control of the indoor environment. Health environment quality needs are taken as constraints. The

system employs logic control mechanisms as optimal management control mechanisms and methods. Logic control mechanisms are described further in section 3.4.

(3) **Outputs**: The outputs automatically adjust the building environmental control system's actuator elements, which include cooling air conditioning, electrically-controlled windows, and mist sprayers. The outputs ensure that comfort is optimal and energy consumption is minimized. (Fig. 8: Photograph of electric air shutter on the 11th floor; Fig. 7: Photograph of central axis electric window on the 8th floor)

System	Elements	Subitems			Content
Building environmental control system	Environmental health information management platform	Inputs	Sensor network	Outdoor climate sensors	1. Temperature, 2. humidity, 3.wind speed, 4. wind direction
				Indoor environmental sensors	1. Temperature, 2. humidity, 3. wind speed, 4. CO_2
				Equipment power consumption	Digital meter
			User interface	Mechanical manual switches	Electrically-controlled windows
				System manual switches	Electrically-controlled windows
				System automatic switches	1. Cooling air conditioning, 2.Electrically-controlled windows, 3. mist sprayers
		Information processor	Database	Real-time data	1. Outdoor climate: a. temperature, b. humidity, c. Wind speed, d. wind direction, e. PMV 2. Indoor climate: a. temperature, b. humidity, c. air speed, d. CO_2, e. PMV
				Historical data	1. Outdoor climate: a. temperature, b. humidity, c. Wind speed, d. wind direction, e. PMV 2. Indoor climate: a. temperature, b. humidity, c. Air speed, d. CO_2, e. PMV
				Equipment operation records	1. Cooling air conditioning, 2. Electrically-controlled windows, 3. mist sprayers
			Control logic		1. Weighted majority voting, 2. if-then
			Environmental quality standards		PMV (fixed threshold)
		Outputs	Output interface	Analog signal	Has this output
				Digital signal	Has this output

Tab. 2: Overview of environmental health information management platform system in the Fu-An Memorial Building.

3.4 Analysis of optimized control logic processes

The environmental health information management platform in the Fu-An Memorial Building employs the weighted majority voting method to assess optimized control mechanisms and methods. The performance indicator settings for the health environment consist of PMV (predicted mean vote) comfort indicators recommended in ISO 7730 (1994), which are intended to ensure optimal control of the thermal air conditioning health environment. [11]

The vast majority of today's architectural environment, thermal comfort systems for independent adjustment of environmental temperature and humidity, but does not perform a comprehensive assessment of thermal comfort. Because these systems do not perform the holistic assessment of thermal comfort, and do not take other influencing factors into consideration, they may keep the air temperature at the ideal temperature, but fail to account for the air flow velocity and humidity, which causes the environment to remain uncomfortable.

The PMV research conducted by Humphreys (1978) and Nicol (1999) [9, 13] indicates that significant differences may exist between the environmental conditions that people prefer in different geographical areas. As a consequence, much statistical analysis may be needed to revise the PMV indicators for a particular environment. This study therefore proposes an optimization control mechanism for thermal environments. By automatically collecting data, estimating actual thermal comfort, and inferring users' desired thermal comfort, this mechanism can automatically adjust environmental quality. It can thus better meet users' needs while enabling effective, reliable use of PMV indicators in the maintenance of a healthy environment. The PMV calculation formula is as follows(1.1):

$$pmv = \left[0.303\exp(-0.036m)+0.028\right]\left\{\begin{array}{l} m-w-3.05\times10^{-3}\left[5733-6.99(m-w)-p_a\right] \\ -0.42\left[(m-w)-58.15\right]-1.7\times10^{-5}m(5867-p_a)- \\ 0.0014m(34-t_a)-3.96\times10^{-8}f_{cl}\left[(t_{cl}+273)^4-(t_r+273)^4\right] \\ -f_{cl}h_c(t_{cl}-t_a) \end{array}\right\} \quad (1.1)$$

- m: is the metabolic rate, in Watts per square meter (W/m2);
- W: is the effective mechanical power, in Watts per square meter (W/m2);
- Pa: is the water vapor partial pressure, in Pascals (pa);
- ta: is the air temperature, in degrees Celsius (□);
- fcl: is the clothing surface area factor;
- tcl: is the clothing surface temperature, in degrees Celsius (□);
- tr: is the mean radiant temperature, in degrees Celsius (□);
- hc: is the convective heat transfer coefficient (W/m2ÅK);

PMV indicators provide average reference values that can be used to assess the comfort of users of an environment on the basis of the six factors of (a) activity level (internal heat production in the body), (b) thermal resistance of clothing, (c) air temperature, (d) mean radiant temperature, (e) relative air velocity, and (f) vapor pressure in ambient air [8]. Some factors, such as activity level (internal heat production in the body), and thermal resistance of clothing are difficult to be measure under real conditions, and this study therefore adopts the reference values (see Tables 3 & 4) proposed in ISO 7730 (1984) and by Olesen (1972) [10,14] as the values for activity level and thermal resistance of clothing:

(a)Activity level (internal heat production in the body): For slow walking (3 km/hr): 116.30 W/m2.

(b) Thermal resistance of clothing: Typical business suit (clo): 1 clo.

(c)

Activity	W/m²	Met
Sleeping	46.52	0.8
Sitting	58.15	1.0
Typing	69.78	1.2
Ordinary standing work in shop, laboratory, kitchen	93.04	1.6
Slow walking (3 km/hr)	116.30	2.0

Tab. 3: Heat production in the body during typical activities
Source: ISO 7730, 1984 [10].

Clothing	Icl	
	Clo	$m^2.℃/W$
Light summer clothing	0.50	0.078
Light tropical suit	0.7	0.110
Typical business suit	1	0.155
Traditional heavy northern European suit with waistcoat, long underwear, and singlet with long sleeves	1.3	0.200

Tab. 4: Thermal resistance of different clothing ensembles.
Source: Olesen, 1972 [14]

PMV	Psychophysical scale
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

Tab. 5: Perceived significance of different PMV values.
Source: Olesen, 1972 [14]

The information processor relies on the coordinated operation of the building environmental control system's actuator elements, which include cooling air conditioning, electrically-controlled windows, and mist sprayers, in accordance with the if-then conditions established by the logic control to improve thermal comfort and reduce energy consumption. This study took the CO2 concentration and indoor/outdoor PMV values as constraints.

(1) Carbon dioxide concentration was used to judge the adequacy of indoor ventilation and air conditioning. Because carbon dioxide is a metabolic product of the human body, a significant rise in carbon dioxide concentration indicates that there is insufficient indoor ventilation. Most countries currently employ the US ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standards (ASHRAE Standard 62-89) to guide design of indoor ventilation and air conditioning systems.[1] ASHRAE ventilation standards specify that each person in a building requires approximately 15-20 cfm of outside air, and recommend that the carbon dioxide concentration does not exceed 1,000 ppm.

(2) PMV indicators provide average reference values that can be used to assess the comfort of users of an environment on the basis of the six factors of (a) activity level (internal heat production in the body), (b) thermal resistance of clothing, (c) air temperature, (d) mean radiant temperature, (e) relative air velocity, and (f) vapor pressure in ambient air. PMV indicators are derived from the subjective assessment of various environmental conditions by numerous test subjects in specific test environments. PMV indicators are expressed on a 7-point scale ranging from -3 (extremely cold) to +3 (extremely hot); the central point (0) indicates the most suitable degree of warmth. Since it is difficult to measure physical activity and the thermal resistance of clothing, these factors are inferred from spatial use behavior

and the season/time, and are considered to be constants in order to facilitate calculation of PMV values. (see Tab.5).

The environmental health information management platform employs the weighted majority voting method to determine optimal control mechanisms and methods (see Table 6). After the system employs weighted majority voting to perform logical operations, it adjusts the state of the system's actuators as needed. This is the mechanism by which the integrity of the system's control logic is maintained. During use, the system uses default settings to judge event triggering conditions, weights, and equipment actions. The system first performs the following environmental control actions in accordance with users' environmental quality and thermal comfort needs. At the beginning of each control cycle, the system relies on the sensor network to detect the ambient temperature, humidity, illumination, air speed, and carbon dioxide concentration, and judges whether any events have occurred. The chief judgment criteria include the following three points:

(1) The first event is judgment of whether the indoor carbon dioxide concentration is too high. The system's default judgment criterion is whether carbon dioxide >1000ppm. If the CO2 concentration is too high, this indicates that there are either too many people in the indoor space or the air conditioning ventilation is insufficient. In this situation, the system will actuate the natural ventilation equipment until the carbon dioxide concentration falls to the lower limit of this setting.
(2) The second event is judgment of whether the outdoor environmental PMV indicator is in the comfort zone. The system's default criterion is: -1.0 <PMV; PMV <+1.0.
(3) The third event is judgment of whether the indoor ambient PMV indicator is in the comfort zone. The system's default criterion is: -1.0 <PMV; PMV <+1.0.

If the indoor and outdoor environments are in the comfort zone, the system will decide whether to use natural ventilation or air conditioning to regulate environmental conditions on the basis of the current indoor microclimate and judgments relying on the system's default values.

Event	Carbon dioxide concentration abnormality	Outdoor PMV is in the comfort zone	Indoor PMV is in the comfort zone	Turn on actuators
Judgment criteria	(CO_2>1000ppm)	(-1.0<PMV; PMV <+1.0)	(-1.0<PMV; PMV <+1.0)	
Weight	Weight: 50%	Weighted: 25%	Weighted: 25%	Majority Weighted >50%
Content status	1	1	1	1(100%)
	1	1	0	1(75%)
	1	0	1	1(75%)
	1	0	0	1(50%)
	0	1	1	1(50%)
	0	1	0	0(25%)
	0	0	1	0(25%)
	0	0	0	0(0%)

1: Event established, 0: Event not established

Tab. 6: Optimized control weighted majority voting in the Fu-An Memorial Building.

3.5 The environmental health information management platform interface

The provision of an appropriate environmental information interface can enhance users' ability to control ambient conditions. Users can employ two types of interfaces in the health information management platform. The type shown in Fig. 9 requires authorization; this screen can be used to select the system operating mode and control the electrically-controlled windows. System operating modes include manual and automatic modes. Electrically-controlled window operating status modes include open electrically-controlled windows and close electrically-controlled windows. In the upper right corner of the screen, "Up one level" takes users to the display screen, while pressing the "Logout" button exits the user mode and returns the system to the general mode. The other interface, which is shown in Fig. 10, is the most commonly used interface, and offers the following main functions:

(1) The currently selected floor is shown on the left side of this screen, and the floor's indoor comfort, temperature, humidity, air flow, and CO2, as well as outdoor temperature and humidity, are displayed on the right side of the screen; the system's current operating mode is displayed above the outdoor environmental parameters.

(2) The status of the electrically-controlled windows is displayed in the lower right part of the screen.

(3) Users can click on another floor on the left side of the screen to call up the display screen for that floor.

(4) Pressing "Go to control screen" in the upper right part of the screen will take the user to the control screen; pressing "Logout" exits the user mode and restores the ordinary mode.

The interface will display a warning when any of the parameter values exceed the safe indicator values, and users should respond to the warning by eliminating the problem. In addition, because the interfaces shown in Fig. 9 and Fig. 10 are both connected with the Internet, as long as users obtain formal authorization, they can obtain the services of remote experts and technicians via the cloud in the event of environmental monitoring situations, parameter revisions, and malfunction.

Fig. 9: Management interface for the environmental health information management platform in the Fu-An Memorial Building.

Fig. 10: Environmental information display interface in the Fu-An Memorial Building environmental health information platform.

4 RECOMMENDATIONS AND DISCUSSION

This study found that the chief functions of an environmental health information management platform enabling optimized control include calculation of PMV indicators for optimal thermal comfort, environmental control minimizing energy conservation, and use of natural ventilation to regulate the building's indoor microclimate. The platform therefore achieves the goal of creating an energy-saving, environmentally-friendly smart building. However, this paper focuses solely on the aspect of optimized control of environmental health, which is discussed as follows:

(1) The environmental health information management platform must be localized, and the design and installation of an optimized control system must therefore consider the characteristics of the local climate and comply with passive design principles.

(2) The design of the control logic algorithm should ensure that the environmental health information management platform will simultaneously provide a healthy indoor environment

and realize optimized control mechanisms and methods minimizing the energy conservation of the building's environmental control equipment.

(3) It is indeed feasible to use an environmental health information management platform to control the indoor temperature and humidity. After deployment, this system provides an optimal, unified means of environmental sensing and control, and can offer users a safe, convenient, healthy, comfortable, environmentally-friendly, and energy-conserving environment.

After system design, it was found that the following future research directions will facilitate practical development:

(1) The environmental health control expert system should be developed: A user interface allowing users to input and adjust environmental control parameters and control methods should be developed, and can provide a platform for expert system development.
(2) A learning mechanism for the information processor should be developed: A learning mechanism for the information processor should keep long-term records of the operating status of actuator elements in the building environmental control system, use efficiency records, and user manual control mode operating records, and use this information to establish a system logic algorithm learning mechanism, and revise the priority weights of rules and events.
(3) Adaptive logic control technology should be developed: Developing adaptive logic control technology will be a key task during the next stage in order to address the conflicts and inconsistencies in the environmental health information management platform's heterogeneous environment.

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