



# New Design and Automation Concept of an Energy-Efficient, Tertiary Building for Mixed-Mode Ventilation System

**Dan William C. Martinez\*** and **Alvin Y. Chua**

*Mechanical Engineering Department, De La Salle University, 2401 Taft Ave., Manila, Philippines*

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\*Corresponding author: [dan\\_martinez@dlsu.edu.ph](mailto:dan_martinez@dlsu.edu.ph)

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**Abstract:** This paper provides a new design and automation concept for tertiary buildings in mixed mode ventilation system with combined functions of mechanical air conditioning and natural ventilation. It aims to make use of simple automation design and set-up to significantly reduce the energy consumption while keeping optimum occupants' comfort. A prototype architectural design of the building aimed at maximizing the passive cooling potential is presented in this paper. The automation system follows a simple control outline where input parameters are fed into a programming control and the system yields the necessary output condition. The system runs in two control operations—schedule-based and event-based—with independent input parameters and with output conditions identified as natural ventilation, full mechanical ventilation, and partial mechanical ventilation. The specific controller, sensors, and actuators for implementing the building automation system were identified. The whole automation concept and design was programmed in an automation software and was simulated to look at the possible system scenarios and results. Results show that a cost saving of as much as Php 246,874.00 per year could be achieved.

**Keywords:** building automation; mixed-mode ventilation; natural ventilation; programmable logic controller

## Introduction

Based on energy reports, it is expected that in 2035 the energy demand of the Philippines will double the 2010 level with about 2.9% average annual increase rate [1]. In 2013, the Energy Policy and Planning Bureau of the Department of Energy has laid and reviewed the Philippine Energy Sector Plans and Programs which aims to ensure the energy security of the country by seven strategic plans and programs. Aside from expanding and localizing the national power supply mainly from renewable sources, one of the programs is making energy efficiency as a way of life among Filipinos to effectively achieve 10% energy saving by 2030 [2]. The Philippine government launched the National Energy Efficiency and Conservation Program as an essential strategy in rationalizing the countries increasing energy demand. Through the program, the energy sector will work on developing and promoting new technologies and the practice of sensible energy habits in homes and in

businesses.

Moreover, the Energy Department implemented the Philippine Energy Efficiency Project which aims to demonstrate the societal benefits of a series of energy efficiency projects in the different sectors: the public, commercial, and residential sectors. One of the key targets of the project was the retrofitting of 135 government buildings with energy efficient lighting systems [4]. Breaking down the energy consumption shares, almost one third of the total energy usage is allocated to residential and commercial purposes that are mainly used for the operations of buildings [5]. In this case, it is important to look at building operations and maintenance to achieve the goal on energy efficiency.

Apparently, energy consumption and environmental comfort in buildings are two contrasting notions that must be equally addressed in building operations. With this, the concept of bioclimatic architecture of buildings has evolved and has been given special emphasis. Bioclimatic architecture is aimed at both energy savings and occupants' comfort and makes use of solar radiation and



natural air flow for natural heating and passive cooling [6].

In building operations, air-conditioning is one of the major energy consumers but is also the primary intervention in providing acceptable ambient conditions for the residents or occupants. Fortunately, natural ventilation or the use of the natural flow of outdoor air may be integrated with mechanical air-conditioning to reduce energy consumption from cooling loads and to potentially improve the ambient conditions inside the ventilated building. Basically, natural ventilation provides openings in building façades to allow fresh outdoor air enter in one area and exit in another for indoor heat removal. Interestingly, natural ventilation may be incorporated with mechanical air-conditioning or the mixed-mode system to extend acceptable climate conditions and to provide energy efficiency in buildings [7].

#### *Mixed-mode Ventilation Studies*

An important review paper was published by J.C. Salcido, A.A. Raheem and R.R.A. Issa [8] which reveals that mixed-mode buildings have the potential to save 40% energy from mechanical air-conditioning by optimizing window operation schedules, and up to 75% by alternating natural and mechanical ventilation. The authors' comprehensive literature review was conducted covering two decades from 1996 to 2016 to analyze the use of mixed mode ventilation systems in office buildings.

Another research paper by K. Hiyama and L. Glicksman in 2015 [9] discussed several natural ventilation strategies including mixed mode systems and explored different aspects and parameters for consideration in the energy-saving system. The paper defined the use of natural ventilation as the building changes between natural ventilation and air-conditioning; and mixed-mode ventilation where the air-conditioning system and operable windows alternately operate.

Previous region-specific studies and investigations on mixed mode have been conducted with focus on optimizing the natural ventilation potential and energy savings. The work of H.M. Taleb in 2015 [10] investigated the potential energy saving prospects of integrating natural ventilation with air conditioning systems into residential buildings of Dubai. Different natural ventilation

strategies were set by varying the degree of air-conditioning and natural outdoor air flow. Overall, the research paper provides insights on the potential savings of various ventilation strategies in a hot climate.

Other studies evaluated energy savings and thermal comfort from mixed-mode system and explored its various strategies. One study used dynamic thermal simulation for evaluating the thermal performance of the building design throughout the year [11]. It was observed from the modelling results that the hybrid ventilation system is a feasible, low energy approach in sub-tropical climates like in their area of case study, south China. One paper explores mixed-mode cooling strategies in buildings with hybrid ventilation and high levels of exposed thermal mass using a full-scale experimental set-up in an occupied institutional building with motorized façade openings [12].

Meanwhile, one study utilized surveys and statistical analysis of occupants' thermal responses during air conditioning and natural ventilation periods; and made observations on the considerable differences in occupants' perceived comfort. The survey findings provide support for a more flexible applicability of the adaptive comfort model in actual building operations and serve as a valuable reference for the design and operation of mixed-mode ventilation [13].

#### *Building Automation Studies*

Improving building operations through automation has been receiving greater attention in recent years because of the potential to reduce energy consumption and to attend efficient building monitoring and maintenance while securing occupants' satisfaction. Building automation system (BAS) is a system installed in buildings that controls and monitors building services responsible for heating, cooling, ventilation, air conditioning, lighting, shading, life safety, alarm security systems, and many more. It aims to automate tasks in technologically-enabled environments, coordinating a number of electrical and mechanical devices interconnected in a distributed manner by means of control networks [14].

Recent papers have been published to propose automation models for the control of energy-consuming systems or installations like HVAC and lightings in buildings and for the monitoring of electrical loads of these systems. One research paper presents a building automation and control tool for remote and real time monitoring of energy consumption in buildings [15]. The proposed tool is based on the optional installation and operation of an automated system of sensors and meters for monitoring and decreasing energy consumption and to rationalize energy use.

**Dan William C. Martinez** is a graduate student of the Master of Science in Mechanical Engineering program in De La Salle University, Manila, Philippines. He focuses his studies on energy and environmental management.

**Dr. Alvin Chua** is a Full Professor of the Mechanical Engineering Department of De La Salle University, Philippines. He earned his BSME, MSME, and Ph.D. in ME at De La Salle University-Manila. He conducted his dissertation research at the University of New South Wales, Australia. He received a special citation for the 2003 NAST-DuPont Talent Search for Young Scientists (Mechanical Engineering). He has published several papers in international conferences like Conference on Decision and Control (CDC), and Advance Intelligent Mechatronics (AIM). His research interests are on mechatronics, robotics, optimal estimation, and controls.



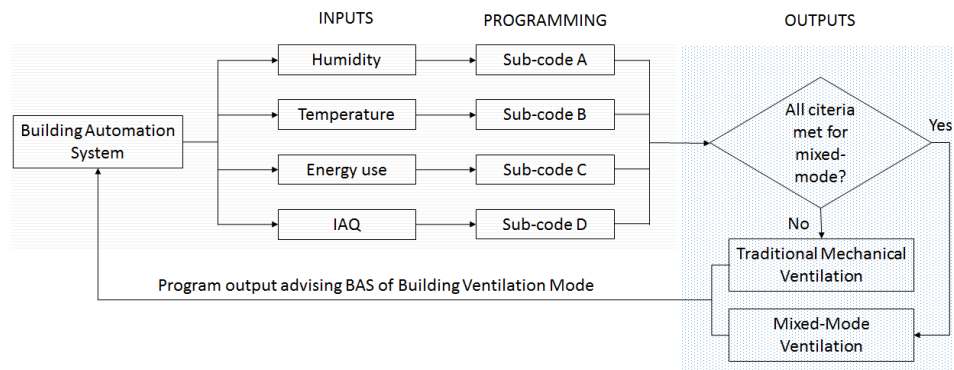


Figure 1. Automated mixed-mode control outline by Menassa et al., [18].

A follow-up paper of the previous publication presents an integrated system for the simulation and optimization of energy consumption in building operation that then allows a supportive tool for the end-users and the interactivity of building automation systems [16]. The proposed system is based on a prototype software tool that can incorporate energy-efficient automation functions. The presented system was applied to a supermarket building in Greece and focused on the remote control of active HVAC systems.

Interestingly, some studies have explored the potential and strategies of mixed-mode ventilation for integration in building automation. A recent publication proposes an occupant-oriented mixed-mode EnergyPlus predictive control system to optimize HVAC energy consumption while meeting the individual thermal comfort preference of the end-users [17]. The study developed four control schemes using a test-bed office building to optimize its energy performance while maintaining the occupant thermal comfort.

Meanwhile, a relevant research develops an automated hybrid or mixed-mode ventilation control for complex commercial buildings and a commissioning methodology which determines the best way to operate a hybrid ventilation system [18]. The methodology was validated through application at the Wisconsin Institutes for Discovery building. The automated control determines whether the space should operate in traditional mechanical ventilation or mixed-mode ventilation based on environmental conditions. In the mixed-mode ventilation system, a BAS sub-routine actuates a series of components to promote natural ventilation. When conditions change and mixed-mode ventilation is no longer feasible, the automated control switches back the ventilation components to initial mode. The framework for the automated control of the study, shown in Figure 1, uses the BAS to monitor three performance metrics: thermal comfort, energy consumption, and IAQ. Actual results show that the system could be used through 28% of the 128-day cooling season resulting in 20% energy savings in comparison to mechanical ventilation.

However, the system was initially designed for temperate climatic conditions where accepted temperature conditions for natural ventilation may exist any time of the day. For hot tropical climates like the Philippines, acceptable temperature condition only exists in certain times of the day: early morning and late afternoon to night time. This situation requires a new automation design concept that allows natural ventilation to work only at those specific times of the day.

This paper presents a new design and automation concept for tertiary buildings in mixed mode ventilation system with combined functions of mechanical air-conditioning and natural ventilation. More so, it aims to make use of simple automation design and set-up to significantly reduce the energy consumption of the designed building while keeping optimum occupants' comfort. The new concept schedules the specific time when mixed-mode ventilation system evaluates the outside environmental conditions for its conditional operation. It also considers scheduling the specific time when only mechanical ventilation, either full or partial, should be relied on for comfort cooling. These considerations are important in areas with hot tropical climate like the Philippines since there are only specific times of the day when natural ventilation is apparently applicable. These important considerations then gave rise to two significant sections in the automation system: schedule-based and event-based operations.

## Architectural Design Consideration

The building in mixed-mode ventilation system to be designed for automation control is a three-story tertiary building intended for residential or commercial purposes which could be an office building, school building, government building or any other building of similar use. Instead of selecting an existing building for case study, the paper provides a prototype architectural design of the building to handle the automation control in order to maximize the cooling potential from the integrated natural ventilation for energy savings. Aside

from reduction in energy consumption due to reduced fan power and air-conditioning load, others benefits of incorporating natural ventilation through façade openings in buildings include: (1) improved indoor environmental quality, (2) reduced capital cost in equipment installation for mechanical ventilation, (3) reduced maintenance and replacement of mechanical equipment for air-conditioning, (4) natural day lighting, (5) increased range of thermal comfort of the occupants, and (6) credits from organizations for energy efficiency.

Natural ventilation inside buildings can be categorized into air pressure ventilation or wind force and stack-effect ventilation or thermal force [19]. Air pressure ventilation occurs when a flow of wind is blocked by a building’s surfaces. The wind’s velocity creates higher pressures on the windward side of the building and lower pressure on the leeward side. This pressure differential then stimulates horizontal air flow in and out of the building for indoor heat removal.

Meanwhile, stack ventilation or thermal force can occur through vertical air movement, where cool air has been warmed up in a building, rises vertically, and is discharged out from the building space. Thermal force occurs due to the difference in density between cool and warm air and can also be created by discrepancies between outdoor and indoor temperatures. However, previous researches agreed that cross ventilation is a more effective approach than stack ventilation in tropical regions where there are no substantial differences in temperature between the indoor and outdoor environments.

With this, only the wind force ventilation, or most commonly termed as cross ventilation, is considered in the adoption of various architectural elements and techniques in the building design to be put under case study. In cross ventilation, the pressure differential is created by three primary factors: (1) wind speed, (2) wind direction relative to the building orientation, and (3) shape of the building [7]. However, one of the main challenges with wind-driven natural ventilation strategies is the unpredictability of wind speed and direction. It is therefore imperative to regularly check wind speed and direction for wind flow induction inside the building before turning into natural ventilation in a mixed-mode ventilation system.

The building for automation control was designed in compliance with the existing architectural building standards of the Philippines and with various passive cooling design strategies to maximize the ventilation potential. The cross ventilation techniques suggested by Aflaki et al in their recent review paper [19] through building façade components and ventilation openings in tropical climates were also applied. The considered

passive cooling and ventilation techniques implemented in the building design include: (1) shading on the east and west sides to avoid sunlight heating especially in the afternoon, (2) raised floor for stronger breeze or wind speed, (3) building orientation at the prevailing angles of wind and sun, (4) size of apertures and windows, (5) narrow form and shape of architectural plan, and (6) ventilated roofs.

In the case of the Philippines, the prevailing winds are Amihan or Northeast Monsoon and Habagat or Southwest Monsoon so the building is oriented along the northeast-southwest line. Also, the location of the building is also crucial for the deployment and maximizing natural ventilation. The location must have good air quality since outdoor air passes through the building, must have good vegetation, and must offer unobstructed wind flow around the building. With this, Balanga City in the province of Bataan was chosen as the prospective location of the automated building. Moreover, only the second and third floors have the integrated mixed-mode ventilation whereas the ground floor has the typical mechanical ventilation system. The building design profile is provided in Table 1.

Table 1. Building Design Profile.

<i>Elements</i>	<i>Specifications</i>
Location	Balanga City, Bataan
No. of Floors	3
Total Floor Area	10 m x 30 m for each floor
Partition	No Internal Partitions
Finished Floor Height	0.50 m
Ground Floor Height	3.0 m
2 <sup>nd</sup> /3 <sup>rd</sup> Floor Height	2.5 m
Fenestration	1.50 m x 0.80 m window size; 6 on NE and SW sides, 10 on SE side, 2 on NW side
Plan &Orientation	Narrow architectural design oriented at prevailing angles of wind and against sunlight

Figure 2 provides the perspective view of the tertiary building whereas Figure 3 provides the orthographic views of the building. The building has a narrow rectangular form in which the building length is three times the building width. There are considerable number of windows in the northeast and southwest sides that will open to allow the flow of the prevailing winds and for better heat removal by moving air. There are only two sets of windows in the northwest side and greater wall area to effectively block the incoming sunlight hitting that side during the afternoon. The suggested building design adopts design suggestions provided by current research studies for maximizing natural ventilation potential.



Figure 2. Perspective view of the designed tertiary building with mixed-mode ventilation.



Figure 3. Orthographic views of the designed tertiary building with the suggested building orientation.

## Automation Concept and Design

The automation concept of this design paper follows the basic definitions, technological pathways and functionalities presented in the review paper on building automation systems by Domingues et al. in 2016 [6]. The review paper is considered a good reference since it was drawn on established literature references to systematize fundamental concepts of BAS prescribed by the ISO 16484-3 or the international standard on building automation and control systems functions and EN 15232 or Energy Performance of Buildings—Impact of Building Automation Control and Building Management standards. In particular, the review paper presented the basic functionality that it is essential in modern BAS listed in the categories: grouping and zoning, event notification, alarm notification, historical data access, scheduling, and scenarios. For simplicity, this design paper adopts the grouping and zoning, scheduling and events categories.

### Building Automation Framework

The designed building automation system follows the control outline shown in Figure 4 where input

parameters are read and fed into a programming control and the system then decides the necessary output condition. Input parameters are grouped into two sections based on the type of automation operation whereas output conditions are identified as natural ventilation, full mechanical ventilation and partial mechanical ventilation. In full mechanical ventilation, all air-conditioning units (A/C units) run whereas in partial mechanical ventilation, only half of the A/C units run. Natural ventilation allows the flow of outdoor air through the building and temporarily replaces mechanical ventilation by opening the windows and shutting off the A/C units when environmental conditions are met. Also, the building reverts back to mechanical ventilation when environmental conditions are not satisfied and the necessary air flow cannot be achieved.

The two different automation system operations are schedule-based and event-based. It is assumed that the tertiary building operates from 7:00 a.m. to 8:00 p.m. or for thirteen hours per day. Between 11:00 a.m. and 4:00 p.m., schedule-based operation works where the sole input parameter is the air-conditioning units' energy load and the output condition is either full mechanical ventilation or partial mechanical ventilation.

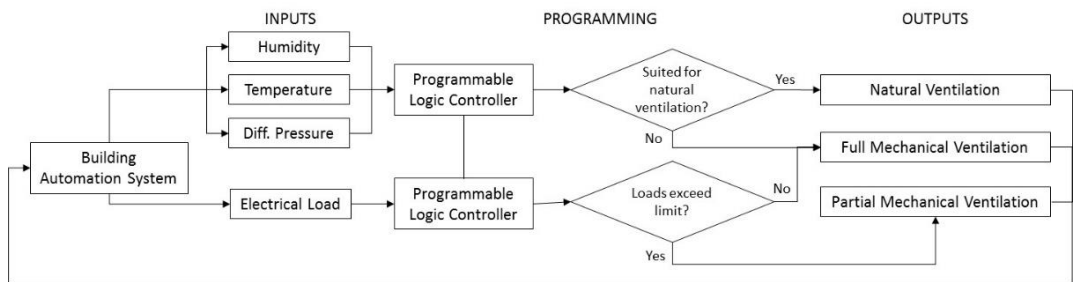


Figure 4. Building Automation Control Outline.

In both ventilation conditions, all windows are closed. Meanwhile, before 11:00 a.m. and after 4:00 p.m. the building works under event-based operation where three input parameters are read and natural ventilation may be incorporated when environmental conditions allow. The system may switch back to full mechanical ventilation when requirements for outdoor air conditions are not met.

Under schedule-based operation, the total electrical load, or energy consumption of all the air-conditioning units are read to determine if it exceeds a predetermined limit. The building initially operates at full mechanical ventilation. If the electrical load reading falls below the load limit, all A/C units keep operating to give full mechanical ventilation. If the load exceeds the energy consumption limit, half of the A/C units are shut off. This set-up allows assured energy savings by limiting the electricity consumption when the electrical load reading goes too high. To assure that acceptable occupants' comfort are provided when the load reading goes down to acceptable level, the system monitors the total electrical load every twenty minutes and decides whether to rerun all the A/C units or to continually shut off some units. In event-based operation, three input parameters are considered for employing natural ventilation during the

morning and afternoon-to-night operation of the building. The system reads the humidity level and temperature level of the outdoor air to ensure acceptable condition to occupants and the pressure differential between inside and outside air to assure sufficient air flow through the building. The system initially runs all the A/C units with all windows closed or initially in full mechanical ventilation. When acceptable air humidity and temperature and the enabling pressure differential are sensed by the system, it shuts off all the A/C units while the windows on the northeast and southwest sides of the building open. There is a lead time of two minutes between the shut off of the A/C units and the opening of the windows. This is to ensure that all A/C units are not in operation while the windows are open and because there is still residual cooling from A/C units few minutes after shut off.

When just one of the three input parameters or environmental conditions is not satisfied, all A/C units remain running with no windows open. The system keeps rereading the input parameters every thirty minutes during the whole event-based operation. Meanwhile, all windows close and all A/C units initially run when the schedule-based operation comes in at 11:00 a.m. Figure 5 provides the adopted automation framework or flow of the building automation system designed in this paper.

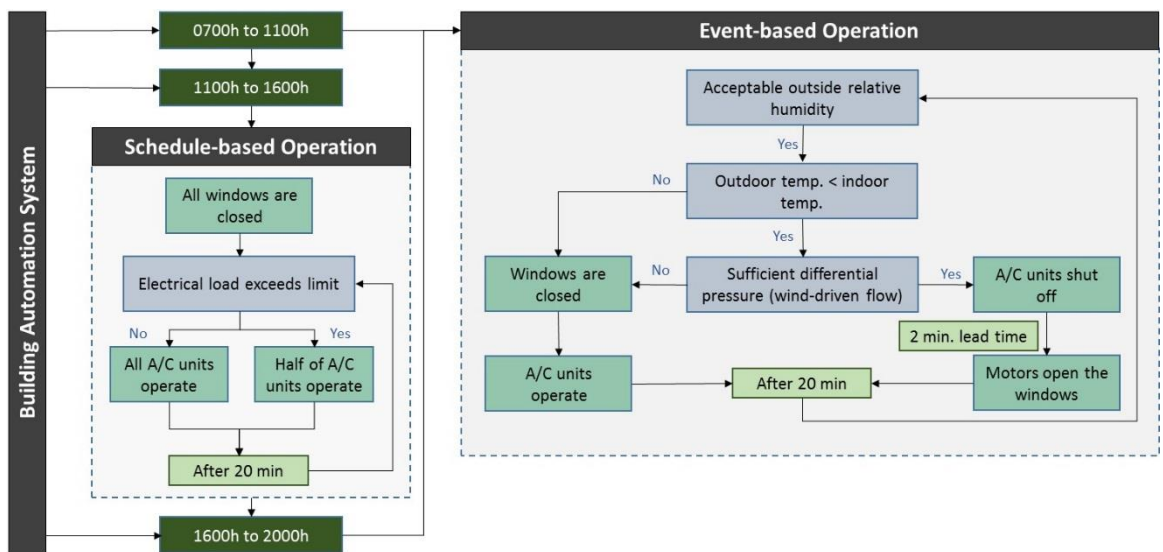


Figure 5. Comprehensive Framework of the Building Automation System.

### Air Conditioning Set-up and Zoning

Based on accepted industry practice, an office space with large interior and a total of 300 m<sup>2</sup> floor area would require 10 tons of air conditioning [21]. With this, each floor will have four wall-mounted, split-type A/C units at 2.5 ton capacity and with recommended energy efficiency ratio of 11 to be situated at four strategic corners of the building as shown in Figure 6.

As part of the automation design, the four A/C units in each floor will be zoned into two: zone A and zone B. Zone A will comprise of the A/C units at the top-left and bottom-right corners of the building as shown in Figure 6, and the remaining A/C units are designated under zone B. During full mechanical ventilation, all A/C units under zone A and B in each floor are in operation. During partial mechanical ventilation, only A/C units in zone A are in operation while those units in zone B are shut off. However, all the A/C units are shut off when the system allows natural ventilation inside the building space.

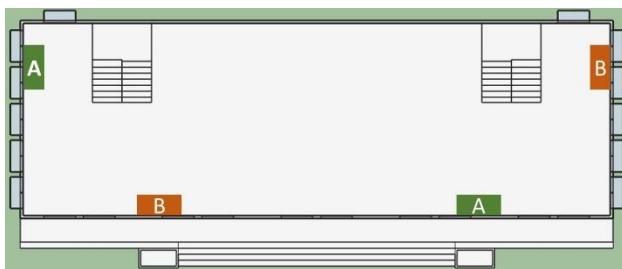


Figure 6. Air-conditioning units zoning for mechanical ventilation.

### Input Parameters Definition

In order to assure acceptable thermal comfort, three input parameters are checked and validated by the system in the event-based operation before the activation of natural ventilation. The acceptable range of outdoor air humidity and temperature are based on ASHRAE Standard 55 or “Thermal Environmental Conditions for Human Occupancy” [20]. The automation system checks if the relative humidity is within the allowable minimum relative humidity of 20% and maximum relative humidity of 70% through a sensor located at the building roof. If the outdoor air humidity is within the range, then the sensing device for relative humidity sends a “true” value to the controller.

Outdoor air temperature is another thermal comfort metric that the system needs to validate before allowing outside air to ventilate the building space. The automation system measures and determines if the air temperature outside the building is within the occupancy comfort range through a sensor mounted on the building roof. Temperature comfort ranges are dependent on

occupied and unoccupied hours and are based on the adaptive model defined by ASHRAE Standard 55. The model suggests a minimum of 12.75 °C for unoccupied hours and a minimum temperature ( $T_{min}$ ) for occupied hours to be determined using Equation (1). ASHRAE Standard 55 also suggests a maximum temperature ( $T_{max}$ ) for both occupied and unoccupied periods to be determined by Equation (2).

$$T_{min} = 0.255 \times T_{mean} + 16.4^{\circ}C \quad (1)$$

$$T_{max} = 0.255 \times T_{mean} + 21.4^{\circ}C \quad (2)$$

The mean temperature ( $T_{mean}$ ) in the adaptive model is the average temperature over the past 30 days with a minimum value of 10°C. Using Equation 1 and Equation 2 and adapting the value for mean temperature of 20°C, the minimum for occupied hours is 21.5°C and the maximum for both occupied and unoccupied hours is 26.5°C. It is assumed that the building space will always be occupied throughout its operating hours so the acceptable outdoor air temperature range that the system validates is 21°C to 27°C.

Meanwhile, the third input parameter to attain natural ventilation output condition is the pressure differential between the indoor air in the building and outdoor air when the windows are open. The pressure differential must be equal to certain values in order to facilitate air movement and heat exchange between inside and outside the building. As wind speed decreases the static pressure increases, and vice versa. The air speed on the windward side of the building is reduced as it collides with the building resulting in an increase in the static pressure. Conversely, as the air speed on the top, sides and leeward side of the building increases, the local static pressure decreases that creates a pressure differential through the building. The wind-driven pressure difference can be derived from Bernoulli’s equation [7], that is:

$$\Delta p_w = (c_{p-w} - c_{p-l}) (\rho U_{ref}^2 / 2) \quad (3)$$

where:

$U_{ref}^2$ , time-averaged approach wind velocity in m/s;

$\rho$ , air density in kg/m<sup>3</sup>;

$\Delta p_w$ , pressure difference from ambient in Pa;

$c_{p-w}$ , wind pressure coefficient (windward surface);

$c_{p-l}$ , wind pressure coefficient (leeward surface).

Still based on ASHRAE 55, there is no minimum value of wind velocity for acceptable thermal comfort for occupants but as temperature is increased from the allowed level, commonly at 22°C, an increase in wind velocity is typically required. However, in the case of this

design paper, a minimum wind velocity must be required and validated in order to facilitate natural ventilation through wind flow. Based on the plot of preferred indoor air temperatures at various air velocities [21] and on the previously computed temperature range of 21°C to 27°C, the desired wind velocity is at the range of 0.10 m/s to 0.30 m/s. A value of 0 m/s wind velocity is not allowed because it means no air flow through the building space and no heat removal. With this, the minimum wind speed is set at 0.10 m/s and the maximum at 0.30 m/s.

Plugging in the desired values of wind velocity, the typical design values of wind pressure coefficient of windward and leeward surface at +0.65 and -0.65 and the value of air density at 1.20 kg/m<sup>3</sup> in Equation 3, the pressure differential must be in the range of 0.0078 Pa to 0.0702 Pa. Therefore, in order to allow natural ventilation, the automation system must detect a pressure differential value between 0.0078 Pa and 0.0702 Pa in addition to the previously prescribed range of air relative humidity and temperature for acceptable occupancy comfort.

Moreover, for schedule-based operation the sole input parameter is the total combined load of the A/C units. The eight A/C units, each at 2.5 ton capacity and energy efficiency ratio of 11, from the two floors have an expected combined energy consumption of 21.82 kW. With this, the energy load limit set as the input metric for schedule-based operation is 22 kW that declares whether the building runs in full or partial mechanical ventilation.

#### *Output Conditions Actuation*

The system leads to three different output conditions or ventilation modes depending on the state of the input parameters. The ventilation modes are basically actuated through spindle actuators that slide the windows in fully closed to fully open position and back, and through control switches that turn on and shut off the A/C units. The spindle actuators drive each of the alternate middle windows connected as illustrated in Figure 7. The driving spindle actuators are installed on the sides of each of the actuated windows at the northeast and southeast sides of the second and third floor of the building. This set-up facilitates better mixing of air inside the building space as well as better heat removal. This set-up requires a total of eight spindle actuators for overall building automation. Meanwhile, control switches are integrated in the zoned A/C units in both floors giving two control switches in total, for zone A and zone B.

In schedule-based operation, the actuators automatically close all windows for full and partial mechanical ventilation. The system checks the total energy load of all the A/C units from both floors every twenty minutes to still assure comfort cooling. When the load reading falls below the defined limit, all the A/C units

in zones A and B continually operate. However, when it exceeds the limit, partial mechanical ventilation works where A/C units in zone B in both floors shut off through the control switch. When the total load falls back below the limit, the shut-off A/C units in zone B operate again through the switch to again give full mechanical ventilation.

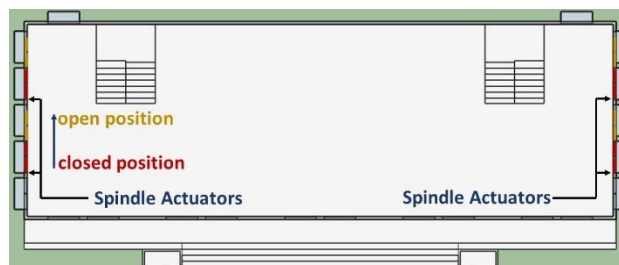


Figure 7. Connection of Actuating Motors to Windows.

In event-based operation, all A/C units in zones A and B are initially in operation and all windows are closed. The system then checks and validates the input parameters. When all the values of all the input metrics fall within the predetermined range of values, all A/C units of both floors shut off through the control switch and after two minutes the spindle actuators open the actuated windows on the northeast and southwest sides of the building. The A/C units remain turned off and the windows are left open until the system revalidates the input parameters after thirty minutes. When the input values still fall within the acceptable range, A/C units remain turned off and the windows open. However, when the input values fall below or beyond the acceptable range, the spindle actuators automatically close all windows and the control switches turn on all the A/C units. The process of revalidating the input parameters and yielding subsequent output conditions happen every thirty minutes until the event-based operation needs to stop and the schedule-based operation needs to come in at a set time of the day.

#### *Controller, Sensors and Actuators*

The building automation design proposes the use of programmable logic controller or PLC for the setting and control of sensing devices for the input parameters and actuating devices to give the necessary output conditions. The design prefers the use of Micro820™ Programmable Controllers of Micro800™ Programmable Controller Family of Allen-Bradley Rockwell Automation. This PLC family is the suggested replacement for the previously popular yet phased out 1760 Pico™ Programmable Logic Controllers and PicoGFX™ Controllers of Pico Controllers Family. The Micro 820™ Programmable Logic Controller Systems are designed for small standalone machine



control and remote automation applications that require flexible communications and I/O capabilities with 36 I/O points. Also, these controllers can accommodate up to two plug-in modules and can connect to a remote LCD (2080-REMLCD) for configuring. [23].



Figure 8. Micro820™ Programmable Controllers.

Meanwhile, the sensing device suggested for both relative humidity and temperature measurement of outdoor air is the INTERCAP® Humidity and Temperature Transmitter Series HMS80 of Vaisala. The specific sensing device is specifically designed for outdoor measurements in various building automation applications, and it therefore fits the need of this automation design. The device includes an integrated radiation shield to reduce the influence of solar radiation on temperature and humidity measurements, which is very ideal since the sensor must be mounted near the building roof. The sensor has a measurement range of 0% to 100% relative humidity and a range of -40°C to 60°C for temperature that cover the needed input parameter range for building automation. The device has options for both current and voltage outputs applicable for microcontrollers, requires low maintenance, and can withstand wind speed of up to 30 m/s [24].

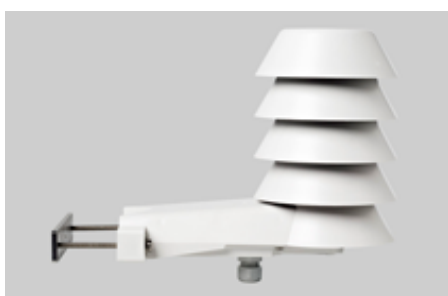


Figure 9. INTERCAP® Humidity and Temperature Transmitter Series HMS80.

For the pressure differential measurement, the sensing device is the Differential Pressure Sensor Type QBM2030-5 of Siemens Building Technologies. The device is used for acquiring even the slightest differential pressure of air or nonaggressive gases in ventilation, air

conditioning, and heating plants. The differential pressure sensors are used to measure over- or under-pressure in air ducts in relation to ambient pressure as well as to monitor pressure differentials between different rooms. In the case of this building automation design, the sensor will be applied in measuring the pressure differential between inside and outside the building space. The device has a measuring range from 0 Pa to 500 Pa atmospheric pressure and transmits 0...10V DC output signal. One duct of the sensing device will be mounted outside the building and the other duct inside the ventilated building space [25].



Figure 10. Differential Pressure Sensor Type QBM2030-5.

In order to implement effective sensing of electrical load, all the eight A/C units in automation are isolated from the rest of the building equipment and appliances and will be monitored by a single, separate energy meter. The SXB Series Energy Meter of Honeywell Building Controls as shown in Figure 11 is the suggested energy meter which can work with a variety of building automation controllers for information and energy-saving flexibility. Moreover, it can measure real-time readings of 26 different points. The sensing device determines and evaluates if the consumed electrical load lies below the defined peak load limit, and dictates the output condition for the schedule-based operation.



Figure 11. SXB Series Energy Meter of Honeywell Building Controls.

To attain the opening and closing mechanism of the windows for natural ventilation, spindle actuators are attached at the bank of the sliding windows. The specific actuating device is the Spindle Actuator 900N Motorlink® (WMS 309-n) of Window Master® as shown in Figure 12.

The spindle actuator may be used together with  $\pm 24V$  control units or control units with MotorLink<sup>®</sup>. The device features synchronization of up to four window actuators which will then enable the automation system to connect the four windows in each floor to work exactly at the same speed and position. Also, the electronics of the spindle actuator can be programmed to suit specific requirements like pressure and traction force, stroke, speed/sound level. It has built-in electronic load switch-off/end stop and electronic actuator with microcontroller. The device slides in a stroke range of 300 mm to 1000 mm and with a pressure and tractive force of 900 Newton. The said specifications conform to the need of sliding the windows in a displacement of 830 mm. The device has a sliding speed of about 5.8 mm/s at full load. The device comes with brackets and fasteners for adjustments in window installation [26].



Figure 12. Spindle Actuator 900N Motorlink<sup>®</sup> of Window Master<sup>®</sup>.

To enable the turning on and off of the mechanical air-conditioning system, the four A/C units under zone A of the two automated building floors are electrically connected in series. The remaining four A/C units under zone B of the two building floors are in a separate series connection. Series-connected A/C units of zones A will have a single control switch as well as the four A/C units from the two floors of zone B. The two control switches for zones A and B are then connected to the controller.

### Programming, Simulation and Cost Savings

#### Ladder Programming Elements and Diagram

The Micro820™ Programmable Controllers of Allen-Bradley Rockwell Automation uses the Connected Components Workbench as its programming software. For the purpose of simplicity and elaborate understanding of automation system simulation, the design paper used the PicoSoft Pro 6 software. Connected Components Workbench and PicoSoft Pro 6 both adopt ladder programming and feature almost similar interface.

Table 6 lists all the programming elements and their representation and functions in the ladder programming for the simulation of the building automation system. Figure 13 illustrates the actual circuit diagram in ladder programming.

Table 2. Programming Elements and Functions.

Element	Representation and Functions
<b>Time Switches</b>	
H01	Event-Based Operation Time Switch
H02	Schedule-Based Operation Time Switch
H03	Off Operations Time Switch
<b>Input Basic Units</b>	
I01	Relative Humidity Input
I02	Temperature Input
I03	Pressure Differential Input
I04	Electrical Load Input
<b>Output Basic Units</b>	
Q01	A/C Units in Zone A Switch
Q02	A/C Units in Zone B Switch
Q03	Windows Closing Switch
Q04	Windows Opening switch
<b>Timing Relays</b>	
T01	Timer for 2-min. delay before A/C units operation
T02	Timer for 2-min. delay windows opening
<b>Markers</b>	
M01	Event-Based Operation Initial Mode (windows closed, A/C units operational)
M02	Schedule-Based Operation Initial Mode (windows closed, A/C units operational)
M03	Off-Operation Mode (windows closed, A/C units turned off)
M04	Event-Based Operation with Input Parameters Activated (windows open, A/C units turned off)
M05	Schedule-Based Operation with Input Parameter Activated (windows closed, A/C units zone B turned off)
M06	Off-Operation Mode (A/C units turned off)

In order to control the building automation at specified time of the day, the program uses 7-Day Time Switches which are H01, H02, and H03. The H01 time switch initializes the event-based operation at exactly 7:00 a.m. and initially sets the building at full mechanical ventilation until input parameters allow natural ventilation. The time switch then ends the event-based operation at 11:00 a.m. and brings the said operation back at 4:00 p.m. up to 8:00 p.m. Time switch H02 does a similar function by initializing the schedule-based operation at 11:00 a.m. until 4:00 p.m. where just either full or partial mechanical ventilation is in operation in the building.

Meanwhile, to control the building condition beyond the event-based and schedule-based operations or when the building is no longer operational, time switch H03 was used to turn off all the A/C units and to secure that all windows are closed. The 24-hour cycle works for

the whole week but the program may be reconfigured to adjust the daily and weekly schedule of building depending on the occupants' needs as illustrated in Figure 14.

The program has four input elements or the four independent input parameters that were defined and were discussed in the previous section. The output units are the switch for the four A/C units under zone A and the switch for the other four A/C units under zone B. The next two output units represent the switches that close and open the windows for natural ventilation through spindle actuators. Timing relays are used to implement a time delay of two minutes before the opening of windows after A/C units shut off and also for the two-minute delay in the operation of the A/C units after the closing of all windows. Markers were used for the effective control of ventilation conditions and for setting the initial building mode at full mechanical ventilation.

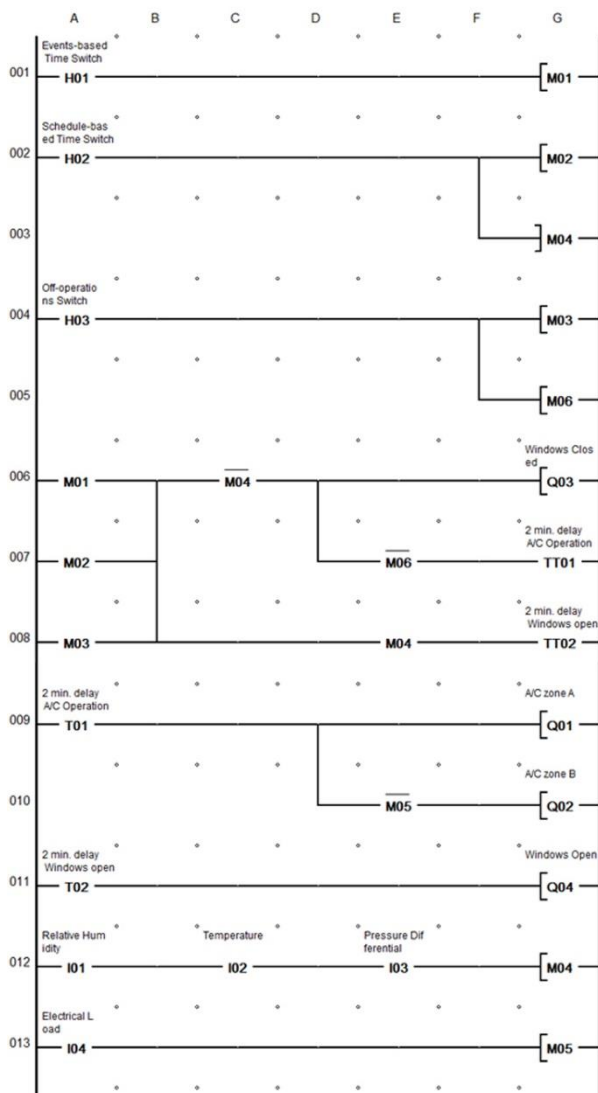


Figure 13. Circuit Diagram of the Building Automation System in Ladder Programming.

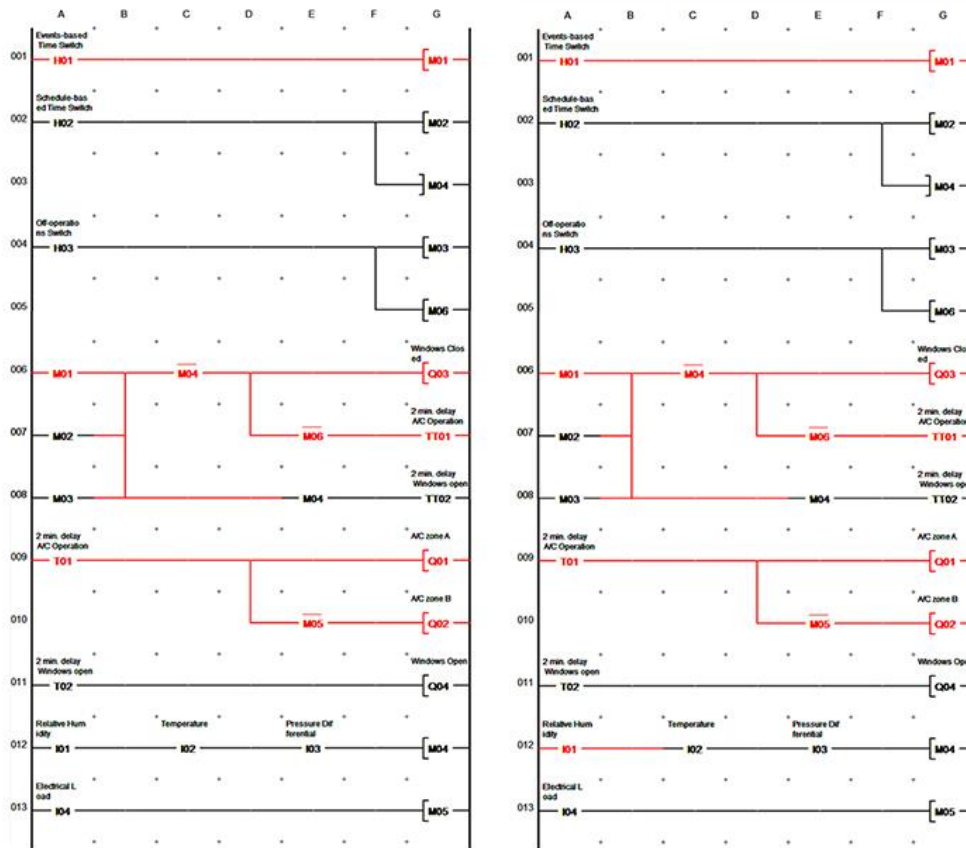
Figure 14. 7-Day Time Switches for Scheduled Building Automation

### Simulation Scenarios and Results

The whole automation concept and design was programmed in an automation software and was simulated to look at the possible system scenarios and results. Time switches turn on the necessary building operation based on a preset schedule and also turns off the devices when beyond the building operating hours. Figure 15 shows most of the operating scenarios that must be attended and may be encountered by the designed building automation system.

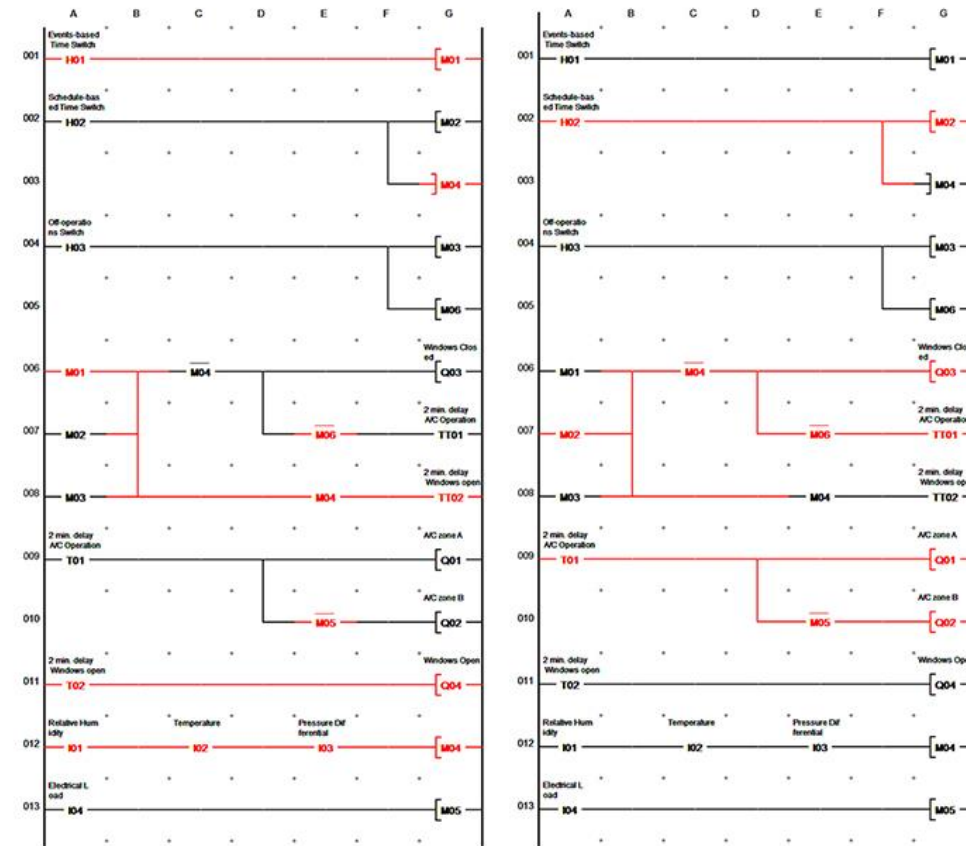
As shown in Figure 15 and Figure 16, simulations (1) to (3) illustrate the output conditions under varying input parameter activations during the event-based operation. The first simulation shows when no input parameters are activated and the second simulation shows when only one input parameter is activated. Both scenarios yield same full mechanical ventilation result where all windows are closed and all A/C units are running. The third simulation for event-based operation illustrates when all the requirements for input parameters are satisfied which allow natural ventilation. In this scenario, all windows are open and all A/C units are shut off.

Simulations (4) to (7) were run for the schedule-based operation. Simulations (4) and (5) were run to show that even when none of the inputs or when any or all of the input parameters are activated, the automation system keeps yielding full mechanical ventilation result. This is the case since under schedule-based operation, only the electrical load input must be read and must be the sole input parameter to dictate the output result.



(1) Event-based operation with no input parameter activated: Windows closed and all A/C units running

(2) Event-based operation with just one of the three input parameters activated: Windows remain closed and all A/C units still running

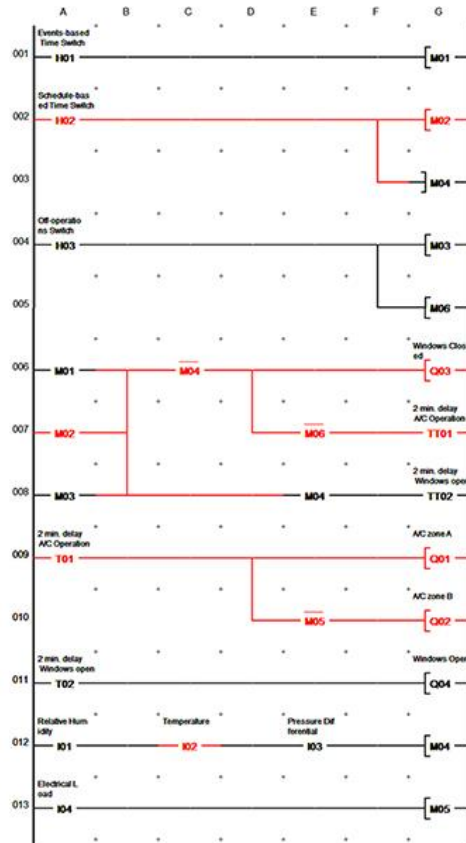


(3) Event-based operation with all the three input parameters activated: Windows open and all A/C units stop operating after 2 minutes

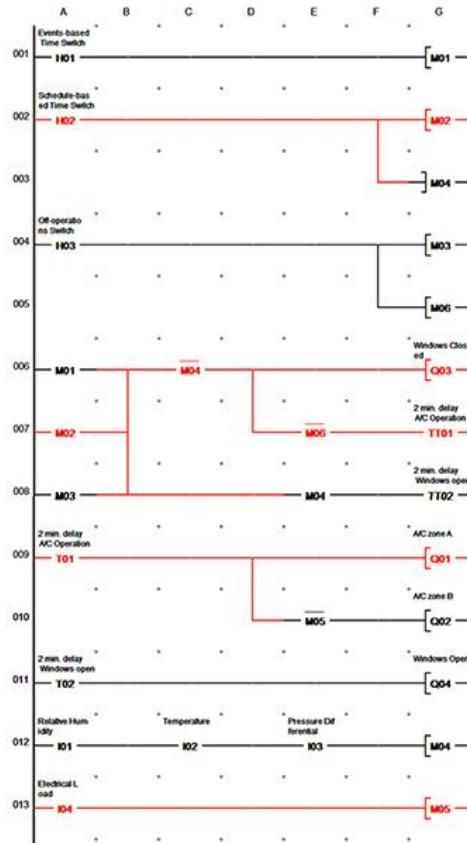
(4) Schedule-based operation with no input parameter activated: Windows closed and all A/C units running

Figure 15. Scenarios (1) to (4) Tested in the Building Automation System Simulation.

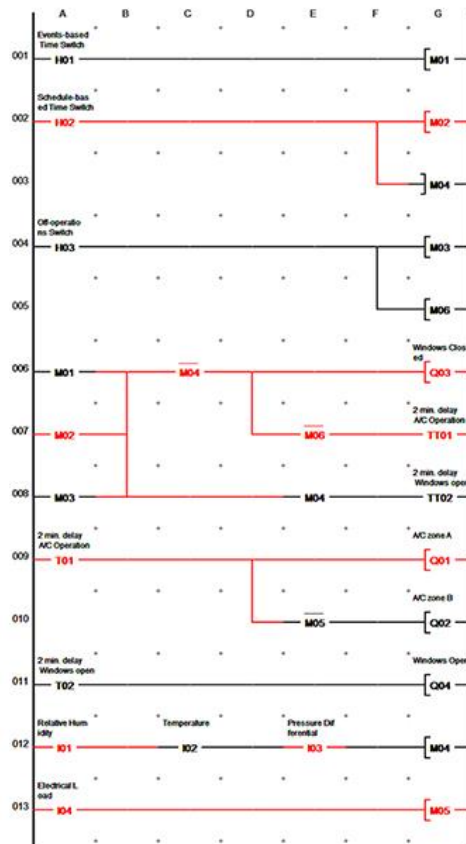




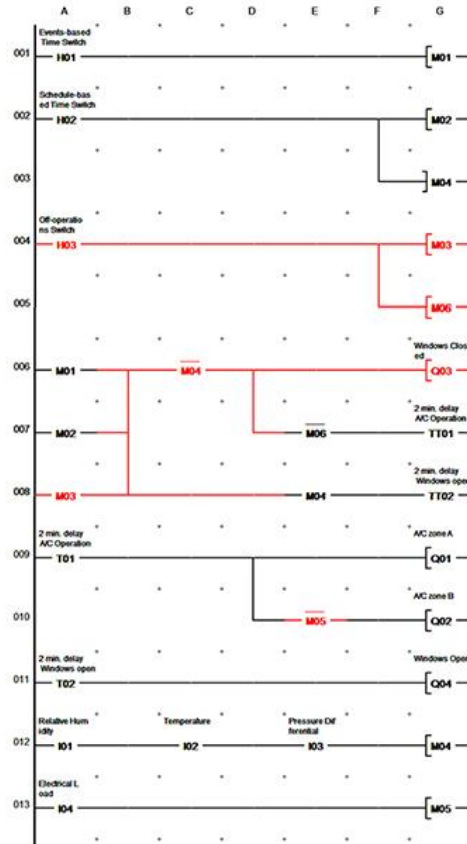
(5) Schedule-based operation with any of the three input parameters activated: Windows remain closed and all A/C units still running



(6) Schedule-based operation with only the load limit input parameter activated: Windows remain closed and A/C units in zone B stop running



(7) Schedule-based operation with the load limit and one other input parameter activated: Windows remain closed and A/C units in zone B still not running



(8) Off-operation mode: Windows closed and all A/C units shut off

Figure 16. Scenarios (5) to (8) Tested in the Building Automation System Simulation.



Simulation (6) shows how the automation system gives partial mechanical ventilation where A/C units under zone B are shut off due to the load limit input parameter being activated. Moreover, simulation (7) illustrates what happens when all input parameters are activated under the schedule-based operation. In this scenario, partial mechanical ventilation is still the output condition where all windows are closed, A/C units under zone A are running and A/C units under zone B are shut off.

Lastly, simulation (8) was run to show the output conditions when the building automation system is off or when it is between 8:00 p.m. to 7:00 a.m. During this time, all windows are closed to secure the building and all A/C units are shut off for complete energy savings.

During the simulation, the system time was set at 7:00 a.m. to test if the time switch for events-base operation actuate the needed operation. At the said time, the time switch initially closes all the windows and turns on all the A/C units to assume full mechanical ventilation. Then the input units: humidity, temperature and pressure differential; are validated. When just one or just two of the three inputs are activated, the system remains at full mechanical ventilation. However, when all the input units are on, the system shuts off all the A/C units of zones A and B and starts opening the windows after two minutes to allow natural ventilation. When just one of the three input units is off, the system brings back the building to full mechanical ventilation where all windows are closed and all A/C units are running. The automation process for the event-based operation ends at 11:00 a.m. and is brought back by the system at 4:00 p.m. up to 8:00 p.m.

### Installation Costs and Potential Cost Savings

In a more practical sense, it is important to look at the economic viability of the presented automation system and to compare the potential cost savings from the reduction of energy consumption. With this, the paper also presents a cost estimation for the installation of the whole automation system as calculated and shown in Table 3. The cost of the air-conditioning system, windows installation and other electrical connection were excluded since they will still be part of the building construction with or without the automation system. The total estimated cost is Php 118,300.00 which includes the automation equipment and materials as well as the labor and supervision cost for installation.

The potential savings from electricity bill due to decreased usage of the air-conditioning system was also calculated. It was previously assumed that the building operates from 7:00 a.m. to 8:00 p.m. and for seven days per week. It is expected that the natural ventilation mode works during the event-based operation, that is 7:00 a.m.

to 11:00 a.m. and 4:00 p.m. to 8:00 p.m., for six months in a year. This assumption would mean that the air-conditioning system will not be operating for 1,464 hours because of the automation system. In comparison, the A/C units will have 4,209 operating hours for the whole year assuming full mechanical ventilation during the whole schedule-based operation and during the entire building operation for half of the year.

All the A/C units have an estimated combined energy consumption of 22 kW that would give a total of 32,208 kW-h energy savings in a year from the automated mixed-mode ventilation system. With the recent effective electricity price of Php 7.6650 for every kW-h in the prospected building location, the estimated cost savings from energy consumption through the automation system is Php 246,874.00 per year.

From this assumptions and rough calculations, it can be concluded that the installation costs for the building automation system can have a payback period of just six months. Moreover, the real impact of the automation system is the decreased energy consumption which responds to the present trust of the government and different communities on energy efficiency and conservation.

Table 3. Estimated Cost of Automation System Installation.

Equipment/Expenses	Cost (in Php)
Micro820™ Programmable Controllers of Allen-Bradley Rockwell Automation	19,100.00
INTERCAP® Humidity and Temperature Transmitter Series HMS80 of Vaisala	12,800.00
Differential Pressure Sensor Type QBM2030-5 of Siemens	6,400.00
SXB Series Energy Meter of Honeywell Building Controls	2,000.00
Spindle Actuator 900N Motorlink® of Window Master® (8 units)	56,000.00
Communication and Electrical Cables	5,000.00
Other Incidental Material Expenses	5,000.00
Labor and Supervision Cost (144 man-hours)	12,000.00
<b>Total</b>	<b>118,300.00</b>

### Conclusion

This paper presents a new design and automation concept for tertiary buildings in mixed mode ventilation system. It aims to make use of simple automation design and set-up to significantly reduce the energy consumption of the building while keeping occupants' comfort. The new concept schedules the specific time when mixed-mode ventilation system evaluates the outside environmental



conditions and when only mechanical ventilation, either full or partial, should be relied on for comfort cooling.

The paper also provides a prototype architectural design of the building to handle the automation control in order to maximize the cooling potential from the integrated natural ventilation.

The designed building automation system follows a simple control outline which flows from input parameters, programming control to output conditions. Input parameters are grouped into two sections: schedule-based and event-based operations, while output conditions are identified as natural ventilation, full mechanical ventilation and partial mechanical ventilation. The necessary input conditions which are ambient temperature, humidity, and pressure differential were defined and set based on existing engineering standards. Window actuations and operations of the A/C units under zones A and B are the controlled parameters for yielding the necessary output conditions.

For the understanding of the automation system, the paper presents the system control through ladder programming in an automation software. Simulations were then run to look at the possible system scenarios and results. The paper shows eight important operating scenarios that must be attended and may be encountered by the automation system. Based on these simulations, the design and automation concept and its suggested set-up can meet the objectives on controlled mixed-mode ventilation in the building.

To look at the economic viability of the actual system and the potential cost savings, a rough cost estimation for its complete installation was presented. The total estimated automation cost is Php 118,300.00 which includes the automation equipment and materials as well as the labor and supervision cost for installation. Meanwhile, the estimated cost savings from energy consumption through the automation system is Php 246,874.00 per year based on recent effective electricity price and acceptable assumptions on the building operations. With this, the overall installation costs for the building automation system can have a payback period of just six months.

However, the most important impact of the automation system is the decreased energy consumption which responds to the present trust of the government and the community on energy efficiency and conservation.

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