CHEMICAL ENGINEERING TRANSACTIONS
VOL. 113, 2024
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Jeng Shiun Lim, Bohong Wang, Guo Ren Mong, Petar S. Varbanov

ISBN 979-12-81206-14-4; **ISSN** 2283-9216
DOI: 10.3303/CET24113022

Multiple Linear Model Analysis of Indoor Air Quality for Air Conditioning System in Office Building

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The building performance is measured through the power consumption of the air conditioning system and indoor air quality (IAQ) of the building spaces to provide sufficient cooling while at the same time satisfying thermal comfort. The multiple linear model of Piecewise linear (PWL) and Multiple Linear Regression (MLR) model is used to accurately estimate the power consumption of the air conditioning system considering IAQ parameters such as carbon dioxide concentration, indoor air temperature, and humidity. The IAQ parameters are usually modelled individually for the building without proper correlation with the power consumption of the air conditioning system. This problem makes the modelling results unrealistic to the building performance solutions. This paper focuses on identifying the relationship between power consumption with integrated IAQ parameters of CO_2 concentration, air temperature, and humidity for Air Conditioning Mechanical and Ventilation (ACMV) system in the office building. The results demonstrate the power consumption estimation model considering IAQ parameters for different time zones is accurate and acceptable with a percentage difference of less than 1 % from the real data. The power consumption estimation model can be used to predict future power consumption with optimum range values for IAQ parameters for sustainable utilisation of energy.

1. Introduction

Multiple linear model analysis is crucial for Indoor Air Quality (IAQ) control in air conditioning systems, especially considering the nonlinear and time-varying nature of ACMV systems. Zulkafli et al. (2022) proposed optimisation methods to improve HVAC operation for chillers, balancing cooling load, efficiency, cost, and comfort. This study uses statistical methods, specifically the Piecewise Linear Model (PWL) and Multiple Linear Regression (MLR), to forecast power consumption trends. It builds on recent literature focused on estimating power usage by analyzing correlations with indoor parameters. By examining data from a well-monitored building, the study assesses zonal temperature and CO_2 levels—key operational and environmental factors. The findings establish a linear model showing the relationship between power consumption and indoor air quality (IAQ) parameters. Young et al. (2023) have been dedicated to creating models for indoor carbon dioxide (CO_2) concentration to maintain indoor air quality. The models use adaptive ventilation control algorithms and machine learning to predict CO_2 levels. Factors like occupancy and ventilation efficiency are considered to design effective ventilation strategies. The proposed model analyses sensor measurements to optimise indoor air quality management. This study aims to identify the correlation between power consumption with IAQ parameters for different time zones by using a PWL analysis with indoor parameters consisting of the relative humidity, number of occupancies, indoor air temperatures, and carbon dioxide (CO_2) concentration as indicators for IAQ. The MLR analysis is conducted to find the coefficient for power consumption estimation that considers three types of IAQ parameters, which are the carbon dioxide concentration CO_2, air temperatures, and humidity.

Paper Received: 11 May 2024; Revised: 6 September 2024; Accepted: 23 October 2024
Please cite this article as: Noordin Saleem S.N.A., Zulkafli N.I., Tee B.T., Sukri M.F., Tahir M.M., Muhajir A., Sulaima M.F., Hanak D.P., 2024, Multiple Linear Model Analysis of Indoor Air Quality for Air Conditioning System in Office Building, Chemical Engineering Transactions, 113, 127-132 DOI:10.3303/CET24113022

2. Methodology

Detailed investigation and analysis of energy consumption with the indoor IAQ parameters in an academic building include three main stages, namely the data collection, PWL correlation, ASHRAE standard analysis and coefficient for power consumption model through MLR analysis.

2.1 Building Description

The research was carried out in the Registrar Office in the Chancellery building located at Universiti Teknikal Malaysia Melaka (UTeM). The building is divided into two thermal zones which are Zone A and Zone B. The occupancy for Zone A is 15 occupants with area of 104.98 m^2 and Zone B is 10 occupants with area of 150.45 m^2. Figure 1 shows the layout for the Registrar Office.
The statistical technique of MLR is employed to model the relationship between a dependent variable with two or more independent variables. The complexity arises in the study of power consumption estimation for ACMV system in a building due to the interaction of several parameters including time zone and building attributes.

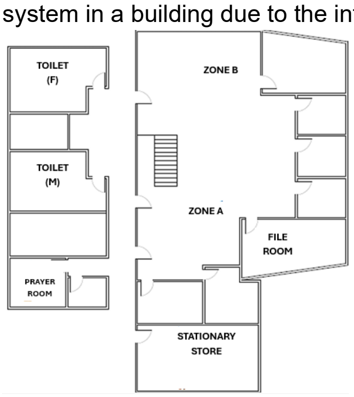

Figure 1: Layout registrar office

2.2 Data Extraction

In the first stage of measurement, data-driven parameters such as power consumption were collected by data logger while carbon dioxide concentration (CO_2), air temperatures, and humidity were extracted from the equipment Kestrel 5400 Heat Stress Tracker (HST) & Weather Meter and were collected manually from the Registrar office. The data was divided into different ranges of power consumption in the morning, afternoon, and late afternoon. The correlation of power consumption with independent indoor parameters was conducted using Piecewise Linear Regression (PWL). In this study, three independent parameters were included: CO_2, air temperatures, and humidity, while power consumption was the dependent variable. MLR was applied to estimate the relationship between two or more independent variables and the dependent variable, which is power consumption. The single model representation for power consumption was obtained by implementing the MLR formula.

2.3 Piecewise linear (PWL) and Multiple Linear Regression (MLR) Analysis

Investigating significant correlations between the identified indoor parameters and the power consumption of the ACMV system can be facilitated by the Piecewise linear model (PWL). PWL is a mathematical framework segregating power consumption into distinct segments or intervals. In this study, the segments are characterized into three time zones, namely in the morning, afternoon, and late afternoon. The correlation of power consumption with pertinent indoor parameters such as CO_2 concentration, air temperature, and humidity is obtained through a linear function for each time zone. PWL has been implemented in numerous domains, including power consumption analysis, which considers the fitting of multiple linear segments to the data, permitting parameters to have varying relationships across ranges. R-squared (R^2) represents the correlation between the dependent variable (power consumption) and the independent variables (CO_2, air temperature, and humidity). The final analysis stage uses MLR analysis to estimate power consumption concerning independent IAQ parameters. The estimation of power consumption for an ACMV system in a building is a challenging task due to the interaction of numerous parameters, such as building characteristics and time zones.

2.4 Standards

The American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) is an organization that establishes the standards and guidelines for designing and operating HVAC systems, indoor air quality, and energy efficiency. The ASHRAE Ventilation Standards 55 and 62.1 provide the guidelines for buildings to operate a healthier, more comfortable indoor environment for occupants while promoting energy efficiency and reducing liability risks. The parameter values based on these standards are shown in Table 1.

Table 1: Parameters in ASHRAE standard

Parameter	Standard	Description
Carbon Dioxide Concentration (CO_2)	ASHRAE Standard 62.1-2016	the recommended CO_2 level indoor buildings in between 500 ppm to 700 ppm
Air Temperature (℃)	ASHRAE Standard 55-2017	temperature range from between approximately 23 ℃ - 25.5 ℃
Humidity (%)	ASHRAE Standard 62.1-2016	recommends that relative humidity in occupied spaces be controlled to less than 65 %

3. Results and Discussion

3.1 Correlation of Power Consumption with CO_2, Air Temperature and Humidity

The next part presents the correlation study of power consumption as the dependent variable using piecewise linear (PWL) modelling. The analysis considers three independent parameters: carbon dioxide concentration, air temperature, and humidity. The PWL trends are classified into three distinct time zone: morning, afternoon, and late afternoon. The data is divided into three separate periods: morning (0900 h to 1200 h), afternoon (1200 h to 1400 h), and late afternoon (1400 h to 1700 h). The data in Figure 2a dan Figure 2b illustrates how these settings impact the energy consumption of the system at various periods throughout the day. The blue colour on the data distribution graph corresponds to the morning zone, whilst the orange colour corresponds to the afternoon zone, and the green colour corresponds to the late afternoon zone. Both chillers in the academic building are currently operating simultaneously.

3.2 Correlation of power consumption estimation with Carbon Dioxide (CO_2)

Figure 2a shows the correlation between power consumption and CO_2. In the morning, the value of R-squared is 0.7056, indicating a positive and strong correlation between power consumption and CO_2. The Zone B in The Registrar office has only 15 occupants.

The highest CO_2 concentration reading for Zone A is 600 ppm at 0810 h which contributes the highest power consumption too which was 122,210 W. This is due to the chiller startup process that consume more energy to cool the building space. 0810 h is the time where the occupant of the office stationed at their workstation. So, the CO_2 concentration has reached the maximum concentration due to the increment of occupancy in the offices. As the time changes, the trendline of the graph shows a strong positive correlation with R-squared value of 0.8203. This indicates a direct good relationship between the power consumption and CO_2. In the afternoon, the average power consumption has reduced to 121,883 W as the chiller power stabilizes during that period and lower power consumption. Referring to Figure 2a and 2b, the reading of CO_2 decreases to minimum value of 500 ppm at 1200 h. This is due to occupants' mobility for lunch break. The reading of the CO_2 has later reduced to 500 ppm. The green trendline represents the late afternoon data with the value of R-squared is 0.7752 for Zone A. The correlation between power consumption for CO_2 has shown a positive and strong relationship for Zone A which R^2 = 0.7256 in the late afternoon. The CO_2 level then increased at 1500 h, with 575 ppm, while the power consumption increased to 122,528 W. The CO_2 increment was due to the high occupancy in the office during that period. Figure 2b shows the correlation between power consumption and CO_2. The R^2 = 0.755 which indicates a strong correlation in the morning. At 0800 h has the highest power consumption that can be observed at 0800 h with the value of 122,210 W due to startup operation. Zone B in the Registrar office has only 10 occupants which is lower compared to Zone A. This contributes to the lower values of CO_2 emissions in the offices. The CO_2 concentration of 360 ppm is the highest in the morning due to the high number of occupants in the office. A strong correlation is shown for Zone B in the afternoon with R^2 is 0.7465 while the CO_2 has reduced to 245 ppm. This is due to a low number of occupants during the lunch break. A strong positive correlation can be observed with R^2 of 0.7256 for Zone B between the power consumption and CO_2 for the late afternoon session. This demonstrates that this period requires more cooling load because of higher radiation heat due to hot surroundings. The values for CO_2 have also increased to 330 ppm compared to the afternoon in line with high office occupancy during that period. Overall, the morning condition in both zones shows a strong positive correlation between power consumption and CO_2. The CO_2 in Zone A are within acceptable average values of 550 ppm, and Zone B represent 321 ppm. This is due to the different number of occupants for different time zones. Zone A has 15 occupants and Zone B has only 10 occupants. It is shown that the lower number of occupants contributes to the lower emissions of CO_2. In the afternoon and late afternoon, a strong negative relationship between power consumption and CO_2, meaning that as the power consumption decreases, so does the CO_2.

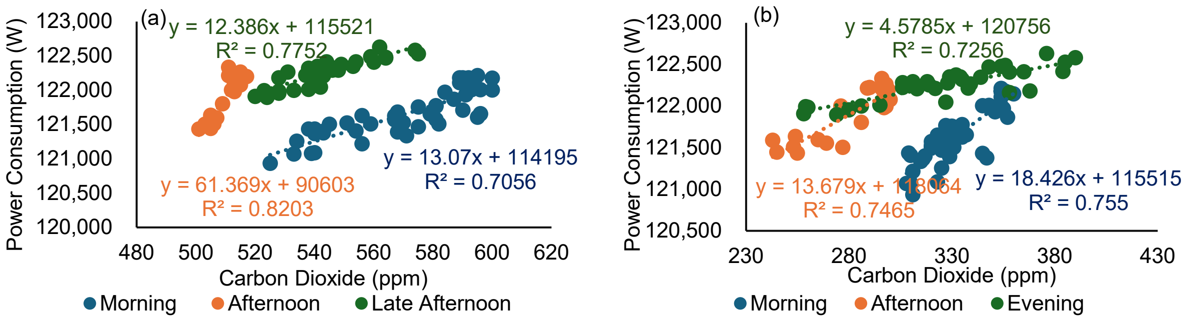

Figure 2: Power versus CO_2 at (a) Zone A and (b) Zone B

3.3 Correlation of power consumption estimation with Temperature

Figure 3a shows a correlation between power consumption and air temperature for Zone A. The graph indicates that R-squared is 0.7178, which represents a strong negative correlation between power consumption and the temperature of the chiller. The highest power consumption of 12,220 W is observed in the morning at 0800 h, when the temperature is at its lowest of 23.8 ℃. This is because chillers require more energy to cool the building during startup. Following a few hours, the temperature begins to rise, accompanied by a discernible decrease in power consumption due to the chillers having reached a stable state. Zone A exhibits a significant inverse correlation during the afternoon, as indicated by an R-squared value of 0.702. This suggests that power consumption decreases as the air temperature rises by 21.3 ℃ at 1300 h. This is because the condenser has stabilised and power consumption is at its minimum in the afternoon. In the late afternoon, there exists a significant inverse relationship between temperature and power consumption. Because more cooling is required towards the end of the late afternoon (i.e., 1700 h), the power consumption is lowest at the beginning of the late afternoon (1400 h) and increases to 23.1 ℃ at the end of the late afternoon (1700 h). Where R-squared is 0.7628, which indicates a robust correlation.

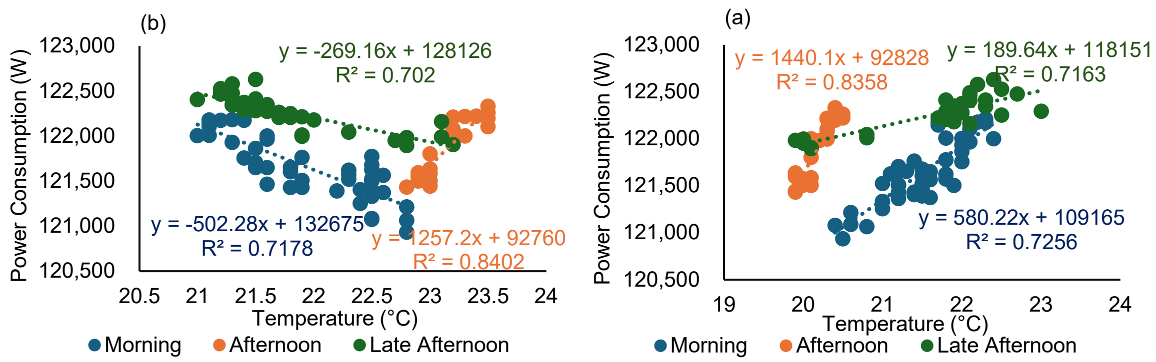

Figure 3: Power versus temperature at (a) Zone A and (b) Zone B

Figure 3b shows the correlation between power consumption and temperature for Zone B. The R^2= 0.7256 has a strong positive correlation between power consumption and temperature in the morning. At 0800 h, the highest power consumption is recorded at 122,220 W due to the chiller's startup operation. The radiation heat content in the morning with the temperature of 22.4 ℃ is lower than in the afternoon and late afternoon. In the afternoon, a strong positive correlation between power consumption and temperature can be observed for zone B, where the average temperature is 20.1 ℃ with the value for R-squared being 0.8358. For the late afternoon, a strong negative correlation is shown with R-squared equal to 0.7163 with the temperature increment to 22.3 ℃. This demonstrates temperature in the late afternoon requires higher radiation heat due to the hot surrounding weather which consumes more power in the late afternoon to maintain the temperature in the office. In summary, the air temperature of Zone A is higher compared to Zone B in the morning, afternoon and late afternoon. This is because of the difference in the temperature between both zones due to the number of occupants where the occupants for Zone A are 15 and Zone B are 10 occupants only. Zone B is much colder compared with Zone A.

3.4 Correlation of power consumption estimation with Humidity

Figure 4a shows the correlation between power consumption and humidity for Zone A. As shown in the figure, the power consumption and humidity in the morning display a negative and strong correlation between both parameters. The highest power consumption is 122,200 W at 0800 h. This is due to the humidity of the office moisture level which was up to 64.4 % as it takes longer time during the chillers startup process. In the afternoon, the trendline of the graph shows a strong positive correlation with R-squared value of 0.7034. This indicates a direct relationship between the power and humidity. As the power consumption decreased, the humidity has increased. At 1230 h, the power consumption for Zone A was 121,883 W (54.4 %), which was lower than in the morning. The humidity does not meet the ASHRAE standard 62.1-2016 which has the risk of mold and mildew growth. Dust mites, bacteria, and fungi all thrive under moist, humid conditions. The green trendline is for the late afternoon with the value of R2=0.7105 for Zone A. The correlation between power consumption for humidity of the chiller is negative and strong Zone A. The power consumption increased again in the late afternoon at 1600 h, with a power consumption of 122,528 W, while the humidity decreased to 64.8 % in line with optimum ASHRAE Standard 62.1-2016. The radiation heat from the surrounding environment increases power consumption during the late afternoon.
Figure 4b shows the correlation between power consumption and humidity for Zone B. A strong negative correlation between power consumption and humidity is observed during the morning. The occupancy level in this zone was lower compared to Zone A. At 0800 h, the lowest power consumption was recorded at 12,220 W and with the humidity of 64 % lower than in the afternoon and late afternoon. In the afternoon, a strong negative correlation for Zone B with the value for R-squared is 0.8358 with a maximum power consumption of 121,883 W and humidity of 55.1 %. For the late afternoon, a strong positive correlation can be observed with R-squared equal to 0.7236 with humidity increased back to 62.2 %. In summary, both zones show a strong negative correlation between power consumption and humidity in the morning. Humidity in Zone A are within an acceptable average value of 64.4 % and in Zone B are 64 %. As mentioned earlier, the zone with a small number of occupants has lower relative humidity levels. Table 2 shows summary of average values for each parameter in different time zones. Based on ASHRAE Standard 62.1-2016, Zone A meets the CO_2 requirements for all time zones while Zone B does not comply with the standard for all time zones. The non-compliance in Zone B attributed to the minimal number of 10 occupants. According to Lowther et al. (2021), lower CO_2 levels are associated with adverse effects on human health, including inflammation, stress responses, kidney calcification, and impaired cognitive functions such as decision-making performance. The suggestion to increase the values of CO_2 concentration by transfer the selected occupants from Zone A to Zone B. Referring to ASHRAE Standard 55-2017, Zone A meets air temperature standard for all time zones while Zone B does not comply with standard at all time zones. The non-compliance in Zone B is attributed to its large area with a low number of occupancies, which contributes to lower temperature effects on the occupants in the neutral conditions that may disturb cognitive performance and body physiological responses as mentioned by Shiva et al. (2021).

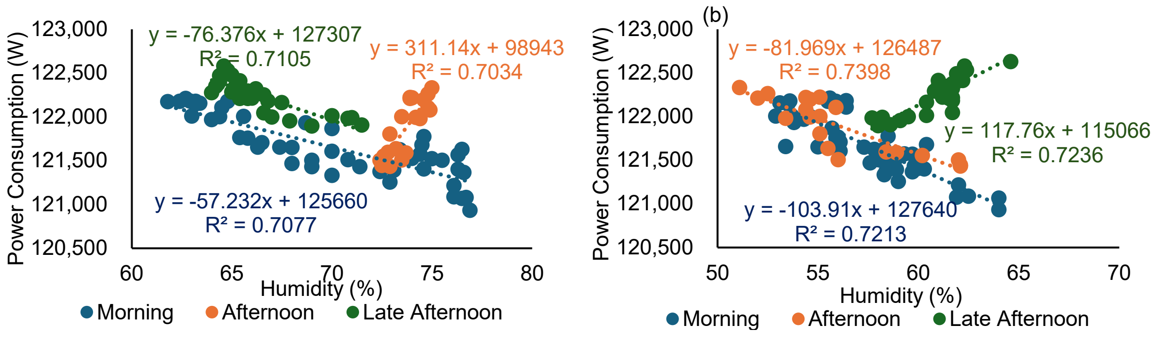

Figure 4: Power versus humidity at (a) Zone A and (b) Zone B

3.5 MLR Analysis

Multiple linear regression (MLR) analysis is conducted to find the coefficient for power consumption estimation that considers three types of indoor parameters, which are the carbon dioxide concentration CO2, air temperatures, and humidity. In MLR analysis, three types of statistical analysis are generated which are the R-squared values, p-values, and coefficient values for MLR model. R-squared measures the proportion of the dependent variable's variance that can be accounted for by the independent variable. A correlation is deemed to be a strong correlate when the R-squared value R^2 exceeds 0.7, as stated by Moree et al. (2013). The MLR analysis is related to P-value to determine whether the power consumption data is statistically significance with the indoor parameters data should be less than 0.05. The general MLR model consists of constant, coefficients, dependent, and independent variables. The Eq(1) and Eq(2) show the linear model to estimate the power consumption. Eq(1) and Eq(2) represent power consumption estimation for Zone A and Zone B, respectively. The χ_{co_2} represents the value for CO_2, χ_{at} represents the value for air temperature, and χ_h represents humidity.

Table 2: Summary of the finding average values each parameter

Parameter	Carbon Dioxide (ppm)		Air Temperature (℃)		Humidity (%)	
Time	Zone A	Zone B	Zone A	Zone B	Zone A	Zone B
Morning	600	360	23.8	22.4	64.4	64
Afternoon	500	245	21.3	20.1	54.4	55.1
Evening	575	330	23.1	22.3	64.8	62.2

3.6 The Real Data and Estimated Data for Power Consumption

The real-time power consumption is obtained from the collected data in the main board electrical power of the building by data logger. The estimated power consumption is calculated from the MLR model in Eq(1) for Zone A and Eq(2) for Zone B. The difference values for both data Zone A is only 0.379 % and Zone B is 0.386 %. Zhao et al. (2020) also support the percentage difference for both chillers has proven the estimated values are acceptable due to a very small percentage difference that is less than 1 %.

$$\gamma_{Zone\ A} = 123004 + (6.42)(\chi_{CO_2}) + (-175.42)(\chi_{at}) + (-16.71)(\chi_h) \quad (1)$$

$$\gamma_{Zone\ B} = 116117 + (7.31)(\chi_{CO_2}) + (252.07)(\chi_{at}) + (-40.37)(\chi_h) \quad (2)$$

4. Conclusion

The multiple linear model to estimate power consumption from indoor air quality of an office building is developed by finding the correlation between power consumption and IAQ parameters for different time zones. The results demonstrate a strong correlation between power consumption and indoor parameters through PWL analysis with R-squared greater than 0.7. The MLR analysis produces coefficients for each IAQ parameter to estimate power consumption with a p-value less than 0.05. The percentage different results for the real and estimated power consumption are compared for Zone A at only 0.379 % and Zone B at 0.386 %. The minimal percentage difference between real and estimated power consumption has proven that the estimated power consumption from MLR analysis can be used to predict future power consumption given that the IAQ parameters can be obtained from measuring instruments. Further studies can be explored to find optimum range values for IAQ parameters for potential energy prediction saving for air conditioning to ensure sustainable energy use with optimum thermal comfort of the building.

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