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Energy and GHG saving potentials of air conditioners (ACs) in a typical commercial building using adaptive controller

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Abstract

In this paper, adaptive data driven controller is utilised to manage energy consumption of Air Conditioner (AC) in a typical commercial banking hall with the aim of reducing electrical energy consumption as well as reduce the carbon emission. The controller has regulatory capability in such a way that the ACs working mode is made to follow the number of occupants and the ambient temperature (time of the day) within the banking hall. In this way, energy consumptions of the ACs are automatically reduced in the time of few customers and cloudy days (low ambient temperature). For effective design of the controller, two sets of primary data (number of people in banking hall per hour and hourly environmental temperature) are collected at a typical commercial banking hall. An algorithm is thereafter developed in java environment and implemented to control the output of the ACs based on the two data sets. Economic and environmental benefits of the proposed controller are also performed. The result reveals that for the typical banking hall an estimated of electrical energy of about 37.2% to 58.2% could be saved using the proposed controller. Moreover, an estimated 2193.84 litres of diesel fuel with the corresponding cost of about $1382.12 could be saved per annum. This cumulates into a saving in CO_2 emission of about 5923.368 kg/yr and CO emission of 16.8048 kg. The study is important as the proposed controller can be built into the thermostat of ACs to make it responsive to the number of customers and the ambient temperature.

Keywords:

Air conditioner, electrical Energy, management, Adaptive controller, Banking hall, GHG emission

Nomenclature

Term	Definition
AC	Air Conditioner
GHG	Green House Gas
CB	Comercial Building
kWh	Kilo-Watt-hour
ATM	Automated Teller Machine
HVAC	Heating Ventilation and Air-Conditioning
CO_2	Carbon II Oxide
IITA	International Institute of Tropical Agriculture
BTU	British Thermal Unit
V	Volume (m^3)
L	Length (m)
B	Breadth(m)
H	Height(m)
E_c	Total cooling energy capacity needed for any given space to maintain acceptable human comfort level per hour (*Btu/hr*)
c_1	Total amount of energy required to cool an empty space per hour (*Btu/hr*)
c_2	Energy required per hour to cool the heat generated by the occupants when room is fully occupied(*Btu/hr*)
k	Energy required for cooling per cubic meter of space per hour ($Btu/m^3/hr$).
q	Heat produced per person(Btu)
N	Ratio of the space area in square meter to the area occupied by 1 person in square meter
η_{ERR}	Energy efficiency ratio: ratio of net cooling capacity or heat removed in *Btu/hr* to the total input rate of electrical power applied in Watt
P_c	Equivalent electrical power required to cool a space(*kW)*
Q_{AC}	Number of ACs required to cool any given space irrespective of the number of occupant
P_{AC}	Available air conditioner rating capacity available in the market (kW)
E_{cool}	Total energy required to cool a space taking into consideration the number of occupants and the ambient temperature
E_{opt}	Energy required to cool depending on the available number of occupant
E_{Tem}	Energy required to cool depending on the ambient temperature (kJ/hr).
$\dot{m}$	Mass flow rate(Kg/s)
c_p	Specific Heat Capacity ($kJkg^{-1}K^{-1}$)
T_o	Ambient temperature (℃)
T_i	Inside air temperature (℃)
$\dot{v}$	Volume flow rate (m^3/s)
ρ	Density of air (1.205 kg/m^3)
A_{CH}	Air changes per hour
v	Volume of air (m^3)
n	Number of occupants (people)
z	Cooling load factor
a	Sensible heat gained per occupant (*Btu/hr*)
b	Latent heat gained per occupant (*Btu/hr*)
$Q_{AC_{Adaptive}}$	Number of ACs required to provide cooling considering the number of occupants and ambient temperature
P_{cool}	Electrical power required to cool the space (*kW*)

$Q_{AC_{main}}$	Numbers of main ACs in the banking hall
$Q_{AC_{backup}}$	Number of ACs on standby (Back-up ACs)
$E_{saved(kWh)}$	Energy saved per day with and without controller (kWh)
t	Time (hour)
M	Number of working hours in the bank per day
S	Savings in Electricity Bills($)
W	number of working days in a year
c_e	Electricity tariff for commercial buildings. ($\$/kWh$)
F_{cool}	Fuel consumed by the diesel generator with controller(*L/hr*)
F_c	Fuel consumed by the diesel generator without the controller (*L/hr*)
A_G, B_G	Coefficients of the fuel consumption curve(L/kWh).
P_{GEN}	Rated power of the diesel geneator required to power the ACs (Kw).
F_{sav}	Fuel saved ($L/hour$)
$F_{sav(yr)}$	Amount of fuel saved per annum($L/year$)
$C_{F(yr)}$	Cost saved on diesel fuel ($)
c_d	diesel price per litter ($/L)
S_{CO_2}	Amount of carbon dioxide per hour (kg/hr)
S_{CO}	Amount of carbon monoxide per hour (kg/hr)
f_{CO_2}	Specific emission of carbon dioxide per litre of fuel
f_{CO}	Specific emission of carbon monooxide per litre of diesel fuel(kg/Litre)
$S_{Carbon(yr)}$	Carbon emission saved per annum (kg/yr)
GUI	Graphical User Interface

1. Introduction

In recent years, energy management in Commercial Buildings (CBs) is gaining increasing attention in academic communities. This is because; the cost of energy usage in CBs is directly built into the cost of their products/services which in turns has negative effect on the finance of the common citizens [1]. Study revealed that energy consumption in CBs is expected to increase faster compared to energy consumption of the residential buildings [2]. This is attributed to the level of comforts required to carry out business in CBs. The energy consumption per square meter of the floor area in commercial building is far above 200kWh annually, having air conditioning system and lightings as the two most energy consuming end-use application within the building [3]. Therefore a considerable amount of energy can be saved in energy efficient buildings by focusing on modelling the thermal behaviour of buildings and designing an optimal control algorithm for the Air Conditioning (AC) systems. Of the various commercial buildings, banking halls are significant because its operation requires huge level of electrical energy consumption for lighting, cooling/heating, computer system, internet provision, ATM machines etc. In most commercial banking halls, the energy consumption is largely unmonitored leading to energy wastage on daily basis, cumulating into high electricity bill. ACs have been identified as one of the major contributor to this energy wastage [4]. It is generally observed that in most banking hall especially in developing countries, all the ACs are turned ON at the start of business till the end of the day's business. The ACs may be in the continuous or thermostatically controlled mode. The same level of cooling are maintained irrespective of the period of the day (ambient temperature) or the number of people in the banking hall. This results in wastage of electrical energy cumulating into high electricity bill, hence there is need for adaptive ACs controller within the banking hall to reduce the wastage whilst keeping an acceptable level of human comfort. Cooling within building is generally achieved through the consumption of electricity, however, high energy efficient building can be achieved if the electricity consumption could be minimized while the required cooling is still maintained. An earlier research [4] showed that 30% of the total load consumption was attributed to cooling. This is huge enough to influence a load curve. It is estimated that energy consumption by heating, ventilation and air conditioning (HVAC) can be reduced on the average by 20%-60% for new buildings with appropriate designs and architectures [3]. Direct load control has also been seeing as one of the important models for demand response. It is always employed to achieve faster and more predictable responses. It is essentially used for thermostatically controlled loads such as HVAC and water heaters. It is estimated that an appreciable energy can be saved by simply applying direct load control method. It is generally believed that effective control of ACs through appropriate demand side management can help achieve optimal comfort level while much energy is still saved [5]. Simulation-based control system is a crucial technology in next-generation modern building systems. This involve the creation of a model that acts like a real building which takes into consideration the physical interaction of the whole building. Various authors have adopted various simulation based control models to gain insight into the electrical energy reduction strategies for ACs: An optimization method using empirically-based models has been proposed by Vakiloroaya *et al.* [6] to achieve energy savings of a cooling system components. The results revealed that about 9% of power consumption by heating, ventilation and air-conditioning (HVAC) can be saved on the average with consideration to human comfort and ambient temperature. Energy savings opportunities have also been studied by Fasiuddin and Budaiwi by selecting appropriate efficient cooling system technology [7]. It was concluded that proper selection of cooling systems can save up 25% of total energy while maintaining acceptable indoor comfort. An experiment has been carried out by Ferreira *et al.* [8]. In their work, they used a model based predictive control methodology to determine the operation of existing HVAC systems in buildings. Their results revealed that about 50% energy could be saved using this method [8]. Lagrangian Relaxation (LR) method has been used in [9] to determine the possible savings in cooling system without sacrificing human comfort. The results show that 24.2% can be saved in an extremely hot day and 20.9% in the cool day. This present work focuses on data driven model developable into a suitable controller that will allocate ACs in a typical banking hall based on population and ambient temperature constraint. The ultimate aim is to minimize cumulative energy consumption while maintaining the desired comfort level

2. Commercial Banking Hall

A typical commercial banking hall houses many air conditioning systems and in almost every time these cooling systems are made to run at full capacity without effective control. Irrespective of time of the day or the number of people in the banking hall, all the ACs are operated at their full capacity. In reality, the operation of the ACs should be in accordance to the number of people and the ambient temperature. In this way, the operations of the ACs are made optimal which increases the electrical energy efficiency of the buildings. Moreover, in most developing nation, most commercial buildings are running on diesel generators due to incessant power failure [10, 11]. Uncontrolled usage of ACs will result into the usage of more diesel fuel, and hence more negative impact due to environmental pollution.

3. Methodology

This section presents data collection for optimal controller design, development of cooling equations, implementation of controller algorithm for a typical banking hall as well as determination of the economic and environmental benefit of the developed controller in terms of electrical energy billing and amount of CO_2 saved.

3.1 Data Collection

The number of people in the banking hall per hour and the hourly ambient air temperature of the day are the two data sets require to developing a good adaptive controller. The daily hourly ambient temperature data observed over a period of 1 year were obtained from International Institute of Tropical Agriculture (IITA) located in Ibadan. Also, the number of people per hour during the official working hours (8:00 hrs to 16:00 hrs) of a typical commercial banking hall were observed every day and recorded for a period of 12 weeks. The average daily data was thereafter determined and is presented in Figure 1. Saturday and Sunday were not considered as banks don't operate on these two days. A trend can be observed in the data, Mondays and Tuesdays present high number of customer inflow compared to other days. This is expected as various businesses usually come up during these two days. Following these two days is Fridays; this is because banks are not in operation on Saturdays and Sundays. Wednesdays and Thursdays experience normal turnout of people in the banking hall. It can however be generally observed that in all the days, the later hours of the day experience more turn out of customers compared to the early hours. Therefore, it is expected that more electrical energy would be needed for cooling on Mondays and Tuesdays compared to the other days. It is also expected that more electrical power would be dispense at the later hours of the day compared to the early hours. Hence adaptive controller that could monitor and follow this trend is required for optimum control of the ACs. For example, electrical energy can be saved in the early hours of the day by decreasing the number of ACs, yet maintaining appropriate cooling in the banking hall at these hours. In the simulation, the number of staff is added to the number of customer per hour to determine the total number of occupant in the bank.

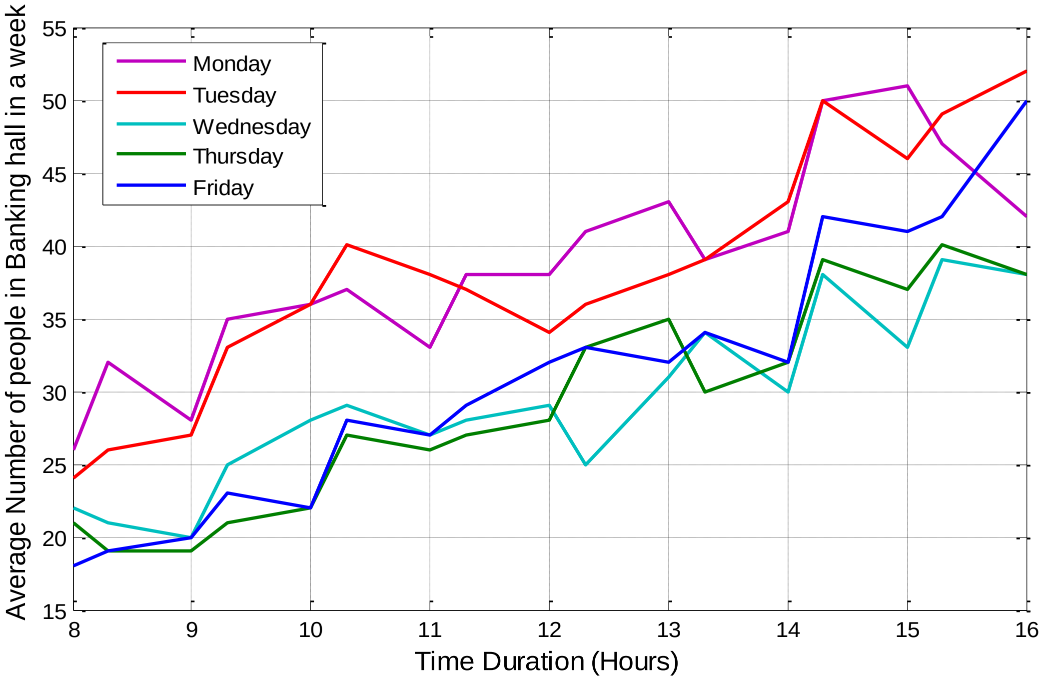


Fig. 1: Average Number of People in Banking Hall in a week.

Similarly, the hourly historical ambient temperature data of Ibadan, where the bank is located was harvested from *IITA*. The data was observed for a period of 1 year and is depicted in Figure 2. Also, the trend in the average hourly temperature can be observed. The figure revealed that in the early hours (8.00–10.00 hours), the temperature ranges between 24–27 °C throughout the working weeks. The temperature is at the peak between the hours of 14.00–16.00 hours. It can be observed that there is a correlation between the customer inflow into the bank and the ambient temperature. Generally, early hours of the day experience lower inflow of customers and lower ambient temperature. Hence, electrical energy can be saved in the banking hall in the early hours of the day.

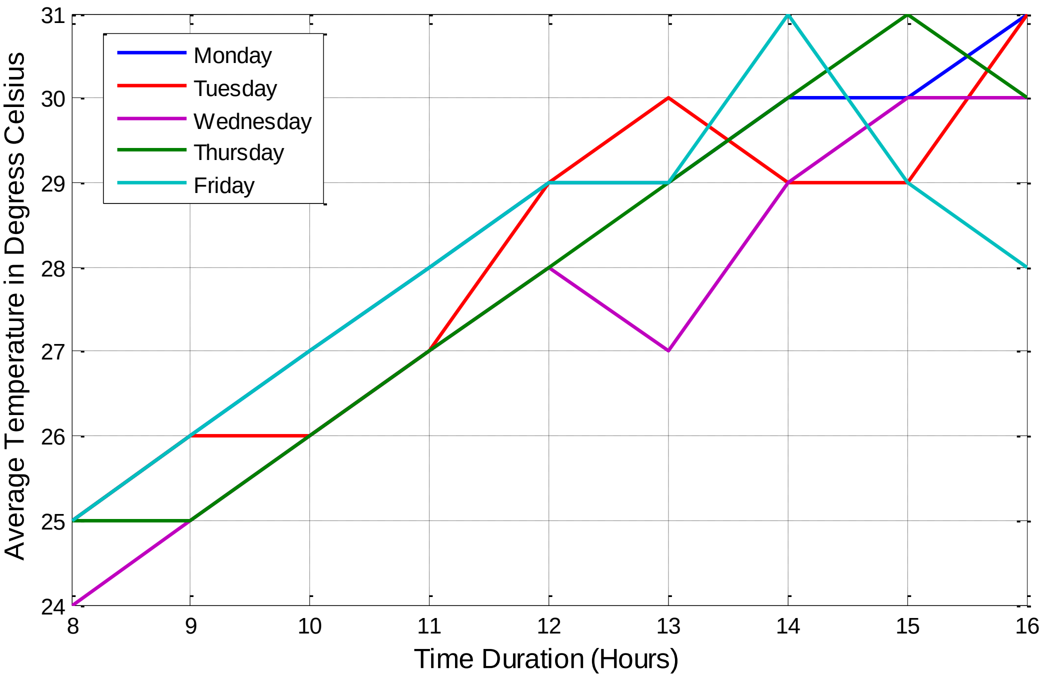


Fig. 2 Average hourly temperature of Ibadan, where the bank hall under study is located.

3.2 Controller Design

In determining the cooling energy requirement in Btu of the ACs, the dimensions of the banking hall are needed to be taking into consideration. This section presents the measured dimension of the banking hall as well as the development of the proposed controller.

3.2.1 The Banking Hall Dimensions

A space dimension is an integral part of the parameters that determine the capacity ACs (i.e. the volume of a space is proportional to the ACs capacity). Hence, the dimension of a space is important input parameters to the design of a controller. The banking hall is divided into 3 sections and each of the sections was carefully measured, the result is presented in Table 1. Non-uniformity in the height of the banking hall was observed from the measurement. Counter height doubled that of the Lobby and Customer service. The Counter is the biggest of all the spaces. This means that highest ACs capacity will be installed at the counter.

Table 1 Banking Hall Dimensions.

S/N	Space	Dimension	Values (m)
1	Counter	Length	16.6
		Breadth	5.3
		Height	5.9
2	Lobby	Length	5.2
		Breadth	5.9
		Height	2.9
3	Customer Service	Length	5.2
		Breadth	5.9
		Height	2.9

3.2.2 Determination of cooling energy capacity without controller

In order to determine the number of Air Conditions (ACs) require to cool any given space to acceptable human comfort, the volume of the space and the energy requirement (*Btu*) to cool the space are determined. Hence, the volume (V) of any space such as a banking hall can be calculated as:

$$V = L \times B \times H \tag{1}$$

where L is the length of the space, B is the width while H is the height of the space.

The total cooling energy capacity needed for any given space to maintain acceptable human comfort level per hour, E_c (*Btu/hr*) assuming every space is filled to capacity can be estimated as:

$$E_c = c_1 + c_2 \text{, } Btu/hr \tag{2}$$

where c_1 is the total amount of energy (*Btu*) required to cool an empty space per hour and c_2 is the Btu required per hour to cool the heat generated by the occupants when room is fully occupied. Both c_1 and c_2 can be estimated as follows:

$$c_1 = V \times k \quad ,Btu/hr \tag{3}$$

$$c_2 = N \times q \quad ,Btu/hr \tag{4}$$

where k is the energy required for cooling per cubic meter of space per hour (Btu/m^3hr). Recent report revealed that, to maintain acceptable level of human comfort, the value of k should be maintained at 6 Btu/m^3hr [12]. Similarly, q is the heat produced per person for a normal office related activities. According to Porges [13], an average person produce about 450 *Btu/hr* of heat for normal office related activity. N is the ratio of the space area in square meter to the area occupied by 1 person in square meter and the area occupied per person is taking as $1m^2$.

Energy efficiency ratio (η_{ERR}) is the ratio of net cooling capacity or heat removed in *Btu/hr* to the total input rate of electrical power applied in Watt. It is usually specified on the nameplate of the ACs by the manufacturer. The range of η_{ERR} for air conditioners is typically about 5.5 to 10.5 and units which have $\eta_{ERR} > 7.5$ are being classified as *high efficiency* units. Therefore, the equivalent electrical power (*kW*) requires to cool a space can be determined as:

$$P_c = \frac{E_c}{\eta_{ERR} \times 1000} \quad kW \tag{5}$$

The ACs used in this paper is the high efficiency units with η_{ERR} of 8.3 *Btu/W* and it is same for all the ACs [12].

The number of ACs required to cool any given space irrespective of the number of occupant can therefore be determined as:

$$Q_{AC} = \frac{P_c}{P_{AC}} \tag{6}$$

where P_{AC} is the available air conditioner rating capacity (kW) available in the market

3.2.3 Development of adaptive controller for the commercial banking hall

From the description of P_c in (5), it can be observed that it is the uncontrollable electrical power (kW) required to cool a space irrespective of the number of occupant and ambient temperature. In this way, electrical power requirement to cool a given space is based on determination of acceptable human comfort assuming the space is filled to maximum capacity at all times. Usage of ACs in this manner could be wasteful especially in a commercial building where the presence of occupant and ambient temperature varies from time to time. To bridge this gap, this paper proposes an adaptive controller that has the capability to follow the number of occupant in a space and the ambient temperature.

Therefore, the total energy required to cool a space taking into consideration the number of occupant and the ambient temperature can be determined as follows:

$$E_{cool} = E_{opt} + E_{Tem} \tag{7}$$

where E_{opt} is the energy required to cool depending on the available number of occupant and E_{Tem} is the energy required to cool depending on the ambient temperature (kJ/hr).

E_{Tem} can be determined using:

$$E_{Tem} = \dot{m}c_p\left(T_0 - T_i\right) \tag{8}$$

Where $\dot{m}$ is the mass flow rate, c_p is the specific heat capacity (1.006 kJkg^{-1}K^{-1}), T_0 is the ambient temperature (°*C*) and T_i is the inside air temperature (°*C*). Equation (8) can be re-written as:

$$E_{Tem} = \dot{v}\rho c_p\left(T_0 - T_i\right) \tag{9}$$

where $\dot{m} = \dot{v}\rho$, ρ is the density of air = 1.205 *kg/m*^{3}and $\dot{v}$ is the volume flow rate and can be re-written as:

$$\dot{v} = A_{CH} \times v \tag{10}$$

where v is the volume of air = volume of the space and A_{CH} is the air changes per hour, it is a constant given as 0.2 for modern buildings [13].

Substitute (10) in (9) yields (11) in *kJ/hr* :

$$E_{Tem} = \left[\rho \times c_p \times \left(T_0 - T_i\right) \times A_{CH} \times v\right] \;\; kJ/hr \tag{11}$$

but 1*Btu*=1.05506 *kJ* , hence (11) can be re-written as:

$$E_{Tem} = \left[1.05506 \times \rho \times c_p \times \left(T_0 - T_i\right) \times A_{CH} \times v\right] Btu/hr \tag{12}$$

Similarly, the energy required to cool depending on the available number of occupant E_{opt} can be determined using:

$$E_{opt} = nz\left(a + b\right) \;\; Btu/hr \tag{13}$$

where *n* is the number of occupant (people), *a* is the sensible heat gain per occupant (250 *Btu/hr*), *b* is the latent heat gain per occupant (200 *Btu/hr*) and z is the cooling load factor, it is a constant taking as 1.0 [13].

Therefore the total energy required to cool a space taking into consideration the number of occupants and the ambient temperature can be written as:

$$E_{cool} = E_{opt} + E_{Tem} = \left[1.05506 \times \rho \times c_p \times \left(T_0 - T_i\right) \times A_{CH} \times v\right] + \left[nz\left(a + b\right)\right] \;\; Btu/hr \tag{14}$$

The electrical power (*kW*) required to cool the space can be determined from (14) as follows:

$$P_{cool} = \frac{E_{opt} + E_{Tem}}{\eta_{ERR} \times 1000} = \frac{\left[1.05506 \times \rho \times c_p \times \left(T_0 - T_i\right) \times A_{CH} \times v\right] + \left[nz\left(a + b\right)\right]}{\eta_{ERR} \times 1000} \quad kW \tag{15}$$

Numbers of ACs required to providing the cooling considering the number of occupants and ambient temperature ($Q_{AC_{adaptive}}$) can be determined as:

$$Q_{AC_{adaptive}} = \frac{P_{cool}}{P_{AC}} \tag{16}$$

3.2.4 Determination of the number of main and back-up ACs in a typical banking hall

In order to make the ACs controller adaptive, the numbers of ACs required by the banking hall are divided into two: The main ACs and the Back-up ACs. The number of main ACs is based on the estimated minimum number of people (customers and staff) and comfortable ambient temperature in the banking hall. The average temperature range for human comfort is taken to be between 18°C to 22°C. The main ACs are turned ON to provide minimum comfort at the start of business and the back-up ACs are made to come up whenever the electrical power (kW) requirement for cooling P_{cool} is in excess of what can be met by the main ACs.

The number of main ACs (QACmain) were recorded ambient temperature at the start of work (8.00 hr) and can be determined by substituting (15) in (16) as follows:

$$Q_{AC_{main}} = \frac{\left[1.05506 \times \rho \times c_p \times \left(T_0 - T_{i_{min}}\right) \times A_{CH} \times v\right] + \left[n_{min} \times z\left(a+b\right)\right]}{\eta_{ERR} \times P_{AC} \times 1000} \tag{17}$$

The number of ACs on standby (Back-up ACs) can therefore be estimated as:

$$Q_{AC_{backup}} = Q_{AC} - Q_{AC_{main}} \tag{18}$$

The flowchart illustrating the controller's activity is depicted in Figure 3 and it was designed and implemented in a Java environment.

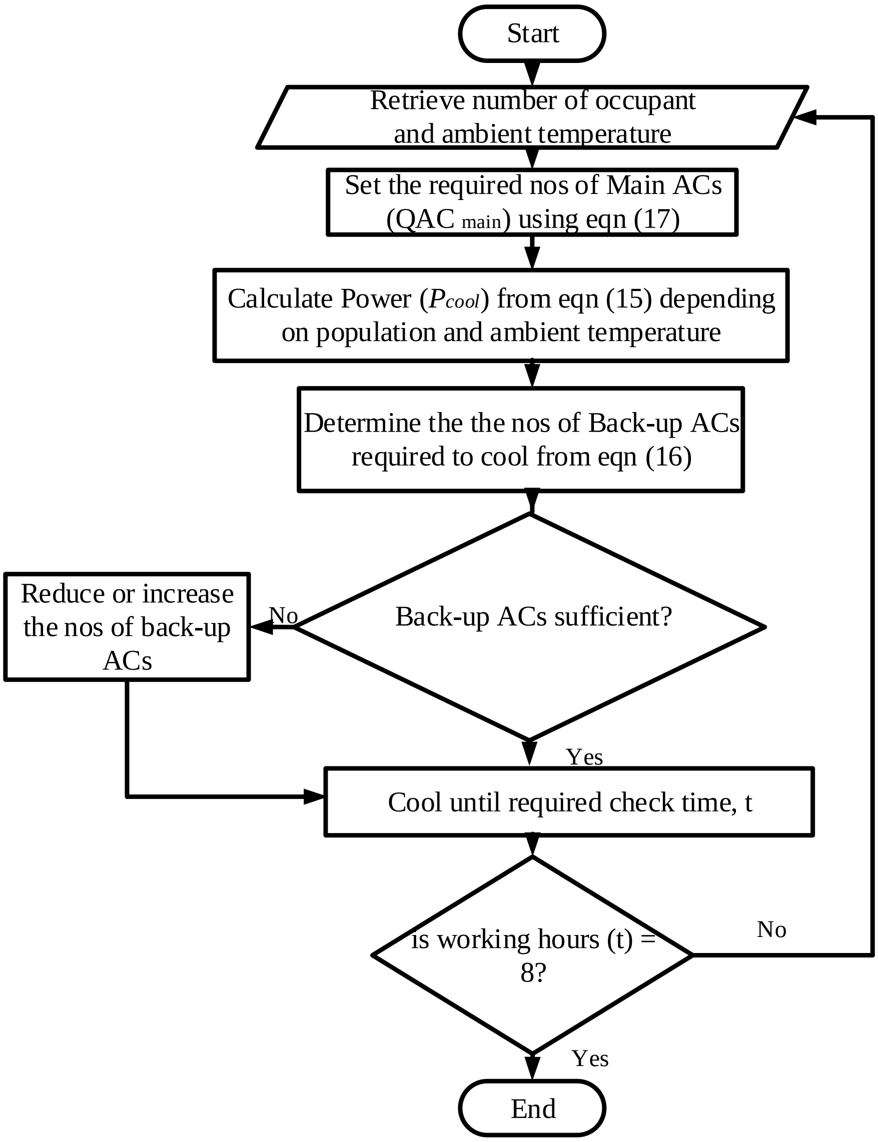


Fig. 3 Flowchart for implementing adaptive Controller.

3.3 Determination of economic benefit of the proposed controller

The energy saved per day (*kWh*) with and without controller (i.e. when number of people and ambient temperature in a space is not considered and when they are considered) can be calculated using:

$$E_{saved(kWh)} = \sum_{t=1}^{M} \left(P_c(t) - P_{cool}(t) \right) \tag{19}$$

where t is time in hour and M is the number of working hours in the bank per day.

Once there is a savings in the energy required for cooling, then, there will also be savings in electricity bill *C* ($) and can be determined as:

$$C = W \times E_{saved(kWh)} \times c_e \ \ \$ \tag{20}$$

where *W* is the number of working days in a year (261 days excluding Saturdays and Sundays) and c_e is the electricity tariff for commercial buildings. The value is set at *$*0.191 per *kWh* [14] by Nigerian Electricity Regulation Commission (NERC)

3.4. Assessment of environmental benefit with(out) the proposed Controller

In most Sub-Sahara Africa e.g Nigeria, most commercial banks run diesel generators to ensure uninterrupted power suply for the smooth operation of all the activities within the banking hall. In this section, the environmental benefit of ultilizing the proposed controller when the ACs in the banking hall are operated on diesel generator is explored.

3.4.1 Quantity of Fuel Consumed by Diesel Generator to operate the ACs with(out) Controller

The quantity of fuel (*L/hr*) that would be required for diesel generator to operate the ACs within the banking hall with or without the controller, respectively can be determined as follows: [15]

$$F_{cool} = A_G P_{cool} + B_G P_{gen} \tag{21}$$

$$F_c = A_G P_c + B_G P_{gen} \tag{22}$$

where F_{cool} and F_c are the fuel consumed in *L/hr* by the diesel generator with and without the controller, respectively. A_G and B_G are the coefficients of the fuel consumption curve in L/kWh. The values has been experimentally determined as 0.246 and 0.08145 [15], P_{cool} and P_c are the electrical power (kW) required to cool the banking hall with and without the controller respectively. P_{Gen} is the rated power of the diesel geneator required to power the ACs in kW. The selection of diesel generator is based on the required electrical energy needed to power all the ACs.

The fuel saved L/hr can therefore be estimated as:

$$F_{sav} = \left(F_c - F_{cool} \right) \tag{23}$$

The amount of fuel saved per annum (L/yr) and the cost saved on diesel fuel ($) can therefore be determined as:

$$F_{sav(yr)} = W \times M \left(F_c - F_{cool} \right) \tag{24}$$

$$C_{F(\mathrm{yr})} = F_{sav(\mathrm{yr})} \times c_d \tag{25}$$

where *M* is the number of working hours of the bank per day and c_d is the diesel price per litter and has the current value of 0.63$/L

3.4.2 Carbon emission saved

The amount of carbon dioxide (S_{co_2}) and carbon monoxide (S_{co}) that would be prevented from polluting the environment per hour *(kg/hr)* when the proposed controller is used can be determined using the followings respectively.

$$S_{co_2} = Sf_{co_2} \times F_{sav} \tag{26}$$

$$S_{co} = Sf_{co} \times F_{sav} \tag{27}$$

Similarly, the amount of emissions that would have been saved per annum can be estimated as:

$$S_{co_2(yr)} = Sf_{co_2} \times F_{sav(yr)} \tag{28}$$

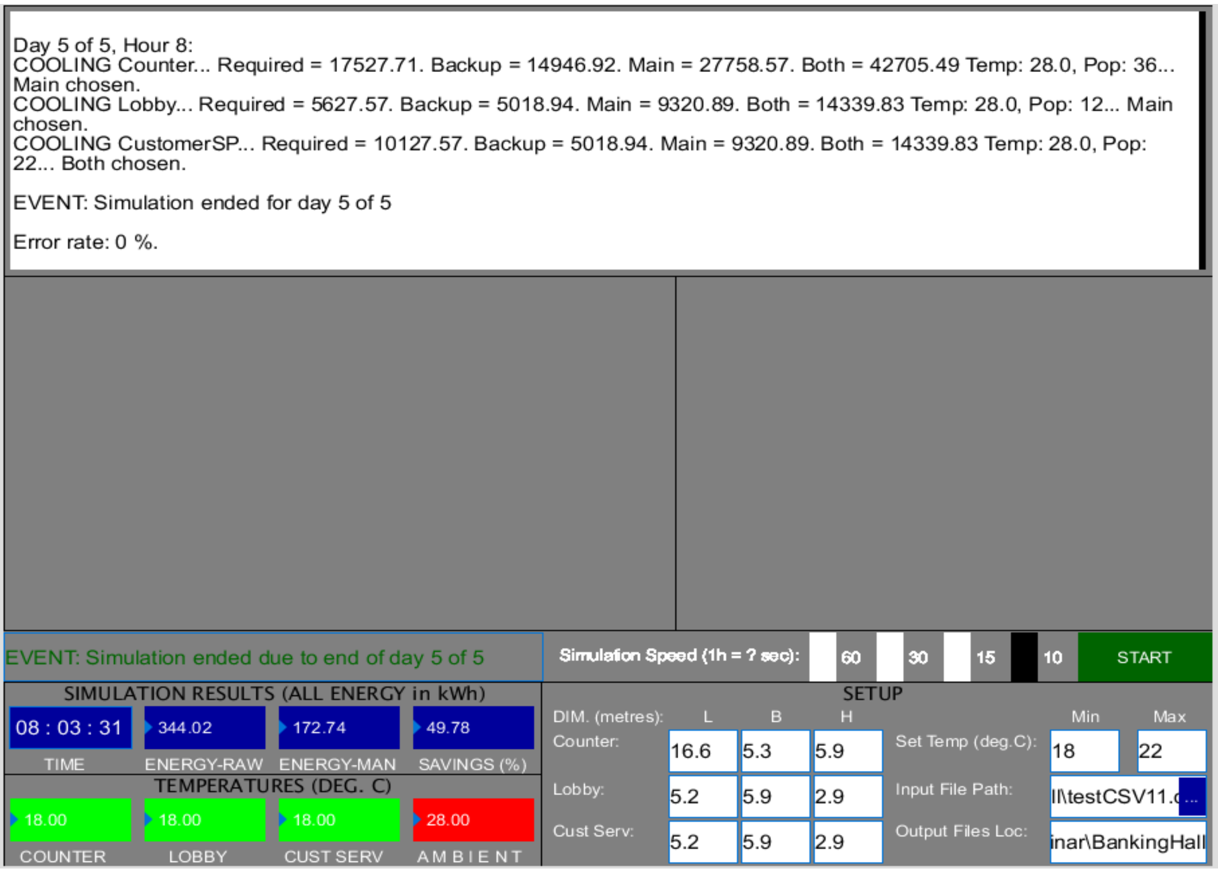
$$S_{co(yr)} = Sf_{co} \times F_{sav(yr)} \tag{29}$$

where Sf_{co_2} and Sf_{co} are the specific emission of carbon dioxide per litre of fuel and carbon monoxide per litre of diesel fuel respectively. The values are given as 2.7 *kg/L* and 0.00766 *kg/L*, respectively [10]. The carbon emission saved per annum can be determined as;

$$S_{carbon(yr)} = 0.27 \times S_{CO_2}\ (kg/yr) \tag{30}$$

3.5 Implementation of the proposed controller in Java Environment

The developed controller has graphical user interfaces (GUI) which accept the input parameters (banking hall dimensions, numbers of occupants and temperature data) and display energy consumption as the outputs parameter. The java-based GUI implementation of the controller is depicted in Fig. 4.



```
Day 5 of 5, Hour 8:
COOLING Counter... Required = 17527.71. Backup = 14946.92. Main = 27758.57. Both = 42705.49 Temp: 28.0, Pop: 36...
Main chosen.
COOLING Lobby... Required = 5627.57. Backup = 5018.94. Main = 9320.89. Both = 14339.83 Temp: 28.0, Pop: 12... Main
chosen.
COOLING CustomerSP... Required = 10127.57. Backup = 5018.94. Main = 9320.89. Both = 14339.83 Temp: 28.0, Pop:
22... Both chosen.

EVENT: Simulation ended for day 5 of 5

Error rate: 0 %.
```

EVENT: Simulation ended due to end of day 5 of 5

Simulation Speed (1h = ? sec): 10

SIMULATION RESULTS (ALL ENERGY in kWh)

TIME	ENERGY-RAW	ENERGY-MAN	SAVINGS (%)
08 : 03 : 31	344.02	172.74	49.78

TEMPERATURES (DEG. C)

COUNTER	LOBBY	CUST SERV	AMBIENT
18.00	18.00	18.00	28.00

SETUP

DIM. (metres):	L	B	H
Counter:	16.6	5.3	5.9
Lobby:	5.2	5.9	2.9
Cust Serv:	5.2	5.9	2.9

Set Temp (deg.C): Min 18 Max 22

Input File Path: ll\testCSV11.c

Output Files Loc: inar\BankingHall

Fig. 4 GUI implementation of the proposed controller.

4. Simulation results and discussion

This section presents the energy saving capability, economic potential and environmental benefit of the proposed controller. The simulation results are based on the data (numbers of occupant and ambient temperature) collected from a typical banking hall. The controller was developed in Java environment based on equations (1)-(18)

4.1 Energy saving capability of the proposed controller

The energy requirement and savings in each of the working hours (8.00-16.00) from Monday to Friday based on the ambient temperature and the numbers of occupant within the banking hall were determined. The results are depicted in Tables 2-6. From the tables, it can be observed that for each hours of each working day, the usage of the controller allows considerable savings in energy. A cumulative energy savings of 25.6253, 40.0698, 33.7865, 36.453 and 34.9095 kWh were achieved on Monday to Friday, respectively. These result into percentage cumulative electrical energy savings of 37.2%, 58.2%, 49.1%, 52.9% and 50.7%, respectively. Lesser energy is saved on Mondays compared to other days. This is expected as more customers visit banks on Mondays as a result of the preceding weekends.

Table 2 Energy Requirements and Potential Savings on Mondays.

			Energy Consumption and Savings		
Hour	Average temperature (℃)	Average no of occupants	Without controller (*kWh*)	With controller (*kWh*)	Energy saved (*kWh*)
Day 1					
8:00–9:00	26	33	8.6006	4.0468	4.5538
9:00–10:00	27	41	8.6006	5.5904	3.0102
10:00–11:00	28	49	8.6006	5.5904	3.0102
11:00–12:00	29	56	8.6006	5.5904	3.0102
12:00–13:00	29	50	8.6006	5.5904	3.0102
13:00–14:00	30	48	8.6006	5.5904	3.0102
14:00–15:00	30	54	8.6006	5.5904	3.0102
15:00–16:00	31	50	8.6006	5.5904	3.0102
Total energy			68.805	43.1797	25.6253

Table 3 Energy Requirements and Potential Savings on Tuesdays.

			Energy Consumption and Savings		
Hour	Average temperature (℃)	Average no of occupants	Without controller (*kWh*)	With controller (*kWh*)	Energy saved (*kWh*)
Day 2					
8:00–9:00	26	22	8.6006	3.0102	5.5904
9:00–10:00	26	25	8.6006	3.5285	5.0721
10:00–11:00	27	18	8.6006	3.5285	5.0721
11:00–12:00	29	13	8.6006	3.0102	5.5904
12:00–13:00	30	21	8.6006	3.5285	5.0721
13:00–14:00	29	37	8.6006	3.5285	5.0721
14:00–15:00	29	19	8.6006	3.5285	5.0721
15:00–16:00	31	43	8.6006	5.0721	3.5285
Total_Energy			68.805	28.7352	40.0698

Table 4 Energy Requirements and Potential Savings on Wednesdays.

Hour	Average temperature (℃)	Average no of occupants	Energy Consumption and Savings Without controller (*kWh*)	With controller (*kWh*)	Energy saved (*kWh*)
Day 3					
8:00–9:00	25	27	8.6006	3.5285	5.0721
9:00–10:00	26	28	8.6006	4.0468	4.5538
10:00–11:00	27	19	8.6006	3.0102	5.5904
11:00–12:00	28	18	8.6006	3.5285	5.0721
12:00–13:00	27	24	8.6006	3.5285	5.0721
13:00–14:00	29	48	8.6006	5.5904	3.0102
14:00–15:00	30	44	8.6006	5.5904	3.0102
15:00–16:00	30	53	8.6006	6.1951	2.4055
Total_Energy			68.805	35.0185	33.7865

Table 5 Energy Requirements and Potential Savings on Thursdays.

Hour	Average temperature (℃)	Average no of occupants	Energy Consumption and Savings Without controller (*kWh*)	With controller (*kWh*)	Energy saved (*kWh*)
Day 4					
8:00–9:00	25	27	8.6006	3.5285	5.0721
9:00–10:00	26	30	8.6006	3.5285	5.0721
10:00–11:00	27	26	8.6006	3.5285	5.0721
11:00–12:00	28	42	8.6006	5.0721	3.5285
12:00–13:00	29	36	8.6006	3.5285	5.0721
13:00–14:00	30	42	8.6006	5.5904	3.0102
14:00–15:00	31	28	8.6006	4.0468	4.5538
15:00–16:00	30	29	8.6006	3.5285	5.0721
Total energy			68.805	32.352	36.453

Table 6 Energy Requirements and Potential Savings on Fridays.

Hour	Average temperature (℃)	Average no of occupants	Energy Consumption and Savings Without controller (*kWh*)	With controller (*kWh*)	Energy saved (*kWh*)
Day 5					
8:00–9:00	26	20	8.6006	3.5285	5.0721
9:00–10:00	27	24	8.6006	3.5285	5.0721
10:00–11:00	28	29	8.6006	3.5285	5.0721
11:00–12:00	29	39	8.6006	5.5904	3.0102
12:00–13:00	29	23	8.6006	3.5285	5.0721
13:00–14:00	31	30	8.6006	3.5285	5.0721
14:00–15:00	29	40	8.6006	5.0721	3.5285
15:00–16:00	28	51	8.6006	5.5904	3.0102
Total energy	0	0	68.805	33.8955	34.9095

The average energy consumption per hour for the whole week within the banking hall with or without the controller was plotted against the working hour and the result is presented in Fig. 5.

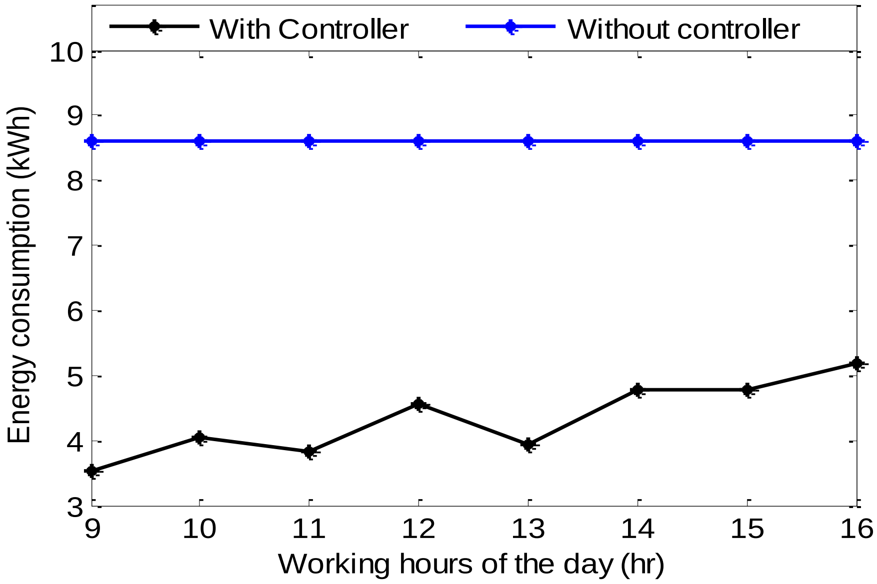


Fig. 5 Average hourly energy consumption with/without controller within the banking hall.

The figure revealed that the energy consumed by the ACs throughout the working hours using the proposed controller is considerably lesser compared to when controller is not utilised. The figure also shows that more electrical energy is consumed at the later hours of the day. This is due to the increase inflow of customers and increase in ambient temperature at this period of the day.

4.2 Adaptive capability of the proposed controller

The population and the ambient temperature within the banking hall are stochastic and it is expected that the controller responds to the variable nature of these two input parameters. Fig. 6 reveals that the controller acted in such a way that the electrical energy requirement of the ACs within the banking hall follows the two stochastic parameters.

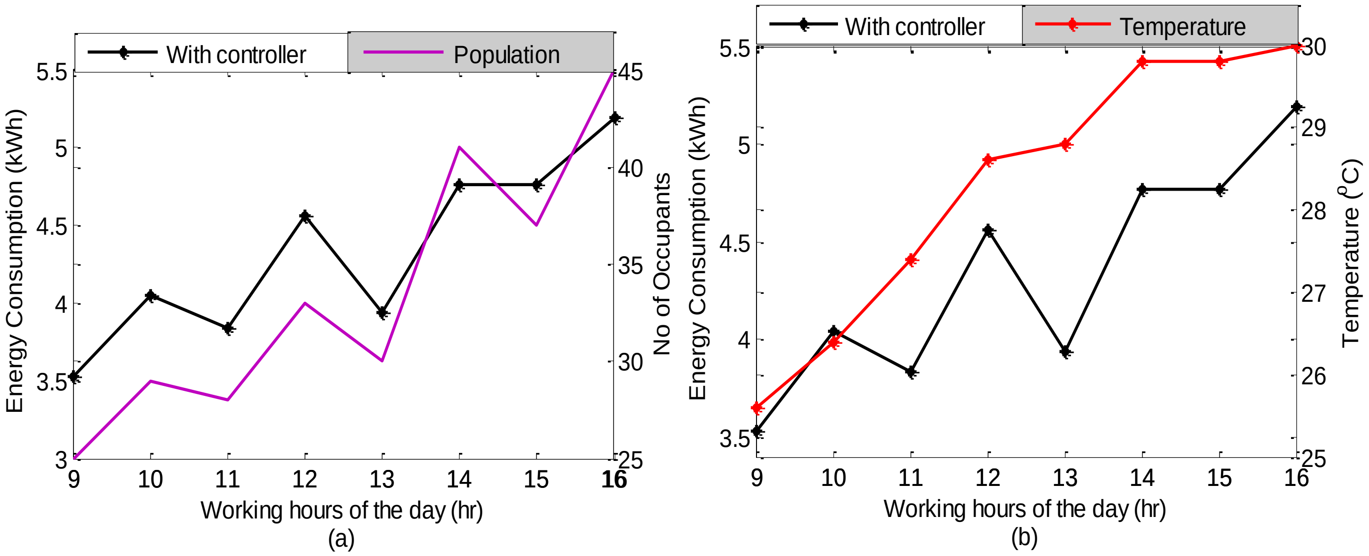


Fig. 6 Adaptive capability of the controller with (a) population within the banking hall (b) ambient temperature.

In this way, the numbers of AC backups increases or decreases according to the total electrical energy requirements. The responses of the energy consumptions by the ACs with or without controller are depicted in Fig. 7. The figure revealed that the energy consumptions by the ACs are controlled in accordance to the two stochastic variables. This reduces the overall energy consumption of the ACs

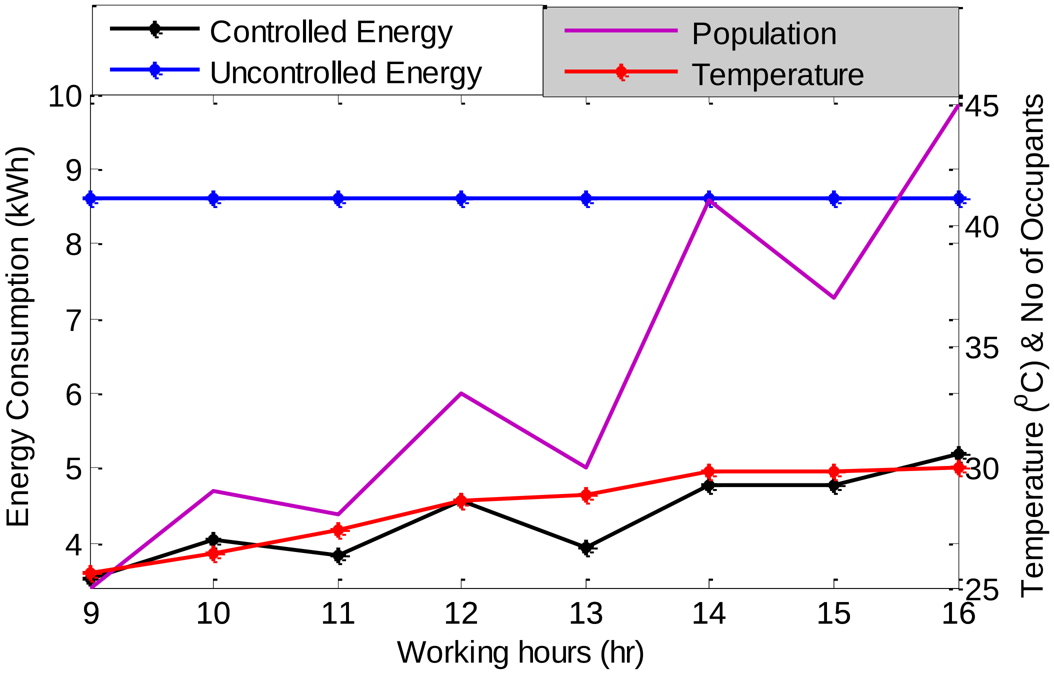


Fig. 7 Energy consumptions by the ACs with or without controller in response to both the population and ambient energy within the banking hall.

4.3 Economic and Environmental benefit of the proposed controller

The environmnetal and the economic benefit of ultilizing the proposed contoller when the ACs in the banking hall are operating on diesel generator is presented. Most banks run on diesel generator to ensure uninterrupted power supply in most Sub-Sahara Africa. The estimated generator ratings at full load to power all the ACs within the banking hall was determined to be 12kVA. Based on this scenario, the amount of diesel that would be saved and the emissions (CO_2 and CO) that would be prevented from polluting the environment are estimated and the result is presented in Table 7. It can be observed from the table that more savings (diesel, emissions and cost) are achieved in the earlier hours of the day. This is because; the number of customers in the banking hall as well as the ambient temperature is low at these periods. Hence, lesser ACs are put into operation by the controller which in turns reduces the amount of diesel consumption and emission pollution of the environment.

Table 7: Average hourly savings in diesel fuel , CO_2, CO and cost of fuel when the proposed controller is ultilised.

			Hourly savings in diesel, emissions and cost				
	F_c	F_{cool}	F_{save}	S_{CO_2}	S_{CO}	S_{carbon}	C_F
Hour	(L/hr)	(L/hr)	(L/hr)	Kg/hr	Kg/hr	Kg/hr	\$/hr
8:00–9:00	2.93025	1.68251	1.24774	3.3689	0.0096	0.9096	0.7861
9:00–10:00	2.93025	1.80946	1.12079	3.0261	0.0086	0.8170	0.7061
10:00–11:00	2.93025	1.75846	1.17179	3.1638	0.0090	0.8542	0.7382
11:00–12:00	2.93025	1.93585	0.9944	2.6849	0.0076	0.7249	0.6265
12:00–13:00	2.93025	1.78396	1.14629	3.0950	0.0088	0.8357	0.7222
13:00–14:00	2.93025	1.98685	0.9434	2.5472	0.0072	0.6877	0.5943
14:00–15:00	2.93025	1.98685	0.9434	2.5472	0.0072	0.6877	0.5943
15:00–16:00	2.93025	2.09254	0.83771	2.2618	0.0064	0.6107	0.5278

The annual savings in diesel fuel, emission and the cost of diesel is depicted in Table 8. The table reveals that 2193.84 litres of diesel could be save per annum which amounts to annual savings of \$1382.12. This results into the prevention of 5923.368 kg of CO_2, 16.8048 kg of CO from polluting the environment, respectively. The annual carbon saving was determined as 1599.3 kg.

Table 8: Annual environmental and economic benefit of the proposed controller.

	Annual savings in diesel, emissions and cost				
	$F_{sav(\mathrm{yr})}$	$S_{CO_2(yr)}$	$S_{CO(yr)}$	$S_{carbon(yr)}$	C_F
Generator Ratings (kVA)	(L/yr)	(kg/yr)	(kg/yr)	(kg/yr)	(\$/yr)
12	2193.84	5923.368	16.8048	1599.309	1382.12

5. Conclusion

In this paper, an adaptive controller that has the capability of following the number of occupants (population) and the ambient temperature has been presented for the management of electrical energy consumption of air conditioners within a typical commercial banking hall. The controller was simulated in a java environment. The simulation results confirmed that a significant amount of energy could be saved by the air conditioners with the use of a controller to monitor the number of occupants and the ambient temperature in a commercial banking hall. The specific result reveals that for the typical commercial banking hall, an estimated of electrical energy of about 37.2% to 58.2% could be saved using the proposed controller. An estimated 2193.84 litres of diesel fuel with the corresponding cost of about \$1382.12 could be saved per annum which cumulates into a saving in CO_2 emission of about 5923.368 kg/yr and CO emission of 16.8048 kg/yr. The controller has been able to minimize cumulative energy consumption while maintaining the desired comfort level. Deployment of this kind of adaptive controller could increase the profit merging of industry as a result of cumulative savings in energy required for cooling.

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