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ORIGINAL RESEARCH ARTICLE

COMPARATIVE ENGINEERING ECONOMIC ANALYSIS OF A VARIABLE REFRIGERANT FLOW AND MINI-SPLIT AIR CONDITIONING SYSTEM DESIGN

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ABSTRACT

The design and comparative engineering economic analysis of two Air-conditioning (AC) systems, mini-split and variable refrigerant flow (VRF), for the new Engineering Complex Building, at the College of Engineering and Environmental Studies, Ibogun Campus of Olabisi Onabanjo University, under the same indoor and outdoor conditions for a one-year period was carried out using Carrier Hourly Analysis (CHA) program software for determining cooling load estimation, and the Net Present Worth Approach for calculating the economic analysis of both systems' design. The cooling load estimation was done using the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) transfer function method rooted within the Carrier software. The total cooling load for the building was found to be 239,243 W. Equipment used in analysis was selected from the Toshiba selection catalogues (Mini Split system), while that for the VRF system was selected using Toshiba simulation software. The annual energy cost analysis of both systems revealed that the VRF system require more energy to run annually than the mini split system. However, the analysis was carried out without considering the part load potential energy savings of the VRF system. Results further indicated from the net present worth analysis carried out, the mini split system, in terms of Net Present Value of both systems, is more favoured. On the bases of the Engineering Economic Analysis carried out on the two systems, the overall Net Present Value for the VRF system was about N78 million, while that of the mini-split system was about N47 million. These results show that the VRF system had a higher cost implication than the mini-split system. Therefore, in terms of cost, the mini-split system was found to be a more viable option being an older and more established technology to the VRF system. In terms of design, the mini-split system, with equal number of indoor and outdoor units, is generally a system with more component units than the VRF system, with less outdoor units to indoor units, was expected to be more complicated and complex in design. However, control and operation flexibilities favour the mini-split system to the VRF system.

1.0 Introduction

The air conditioning systems are a subset of the heating, ventilation and air conditioning systems, popularly known as H-V-A-C systems. Design and selection of air-conditioning systems in the contemporary framework involves lots of factors that are put into consideration for various applications. Generally, when designing and selecting viable Heating, Ventilating, and Air-conditioning (HVAC) systems designers aim to come up with the most efficient HVAC systems which will be appreciated from the architectural perspective, energy consumption angle, installation aspect, indoor air quality, thermal comfort and majorly from the aspect of economics and cost implication. Research Literatures are in abundance on the comparison of performance characteristics of different types of air-conditioning systems (Aynur *et al.*, 2008a, Aynur *et al.*, 2008b, Kim *et al.*, 2016 and Zhou *et al.*, 2017). Aynur *et al.* (2008a, 2008b) noted in their studies that variable refrigerant flow (VRF) air conditioners are noted for high energy saving potentials and are expected to save more energy than other conventional air conditioning systems. Similarly, in the studies of Zhou *et al.* (2017), using the generic dynamic building energy simulation package Energy Plus, developed a new VRF module and investigated the energy usage of the VRF system. A comparative analyses of the energy consumption of the VRF system with that of two other conventional air-conditioning systems, namely, variable air volume (VAV) system as well as fan-coil plus fresh air (FPFA) system were carried out. Simulation results showed that the energy-saving potentials of the VRF system were expected to achieve 22.2% and 11.7%, compared with the VAV system and the FPFA system, respectively. The present study focuses on establishing a comparative analysis between a Variable Refrigerant Flow air conditioning system (which is similar to a multi split air conditioning system) and a Mini Split air conditioning system from the perspective of both design as well as economics.

Brar (2012), developed a new methodology for the evaluation, comparison, ranking and optimum selection of air conditioning systems from different design options. The proposed methodology is based on multi attribute decision making (MADM) approach (Brar, 2012). Relevant features, which describe the whole air conditioning system, were identified exhaustively for the MADM approach. Popovici and Hudişteanu (2015) carried out investigation of the performance of the Heating, Ventilation and Air Conditioning system at "Vasile Alecsandri" National Theatre of Jassy, Romania, for varying external conditions. A 2D simulation model of the building was used to carryout performance analysis with ANSYS Fluent software. The performance of the HVAC system during winter and summer seasons were simulated and analysed for the situation when the entire theatre hall was occupied. Their results revealed and established that the HVAC system provided adequate conditions for both studied seasons.

Barot (2014) reiterated that the main objectives of the HVAC system design are that of providing thermal comfort, good indoor quality and energy conservation. However, some special HVAC projects may not be necessarily energy-efficient in daily operations due to their operations requirements, specific design and control of the HVAC the system. The design and equipment selection of the HVAC system for a commercial building (with required cooling capacity of 376 TR) was studied. The results of the study of Barot (2014) revealed efficient air conditioning methods (water cooled screw chiller, air cooled screw chiller, conventional split ac units and air cooled VRF system) for the design of HVAC systems with minimum energy consumption and equipment selection based on operating and life cycle cost analysis.

1.1 Statement of problem/ Purpose of Study

Buildings have a characteristic exterior air temperature, known as the balance point temperature, at which the building in use would be able to maintain thermal comfort without the need for a heating or cooling system. At the balance point temperature (strongly influenced by internal loads, solar influence and envelope design) building heat gains and losses are in equilibrium so that a suitable interior temperature be maintained naturally. However, when the outside air temperature drops below the balance point temperature, heat losses through the building envelope will increase, and interior air temperature will drop unless heat is added to the building to compensate for the heat losses from the building, which is accomplished by a space (or building) heating system. Likewise, when the outside air temperature exceeds the balance point temperature, heat gain through the building envelope will upset thermal equilibrium and cause the interior air temperature to rise. A system that removes such excess heat is called a cooling/air conditioning system.

Due to an increase in the outdoor temperature as well as consistent indoor temperatures above the balance point temperature, a system needs to be designed that will effectively offset the heat gains into the spaces in the OOU College of Engineering Complex Building, while saving energy in the process. Moreover, to maintain a proper Indoor Air Quality, contaminants which include radon, Moulds, allergens, Carbon Monoxide (CO), Volatile Organic Compounds (VOC), Legionella, Asbestos fibres, CO2, among others, need to be diluted by proper ventilation methods, which also needs to be energy efficient.

Hence, this study aims to design an energy efficient and environmentally friendly air conditioning and ventilation system for the complex building. And to achieve these purposes, two air conditioning systems are compared, which are the VRF and mini split air conditioning systems.

The objectives of the study are:

Carryout a site survey and determination of the various environmental parameters.

Carryout space audit and determination of cooling loads of the various zones of the building complex.

Design Analysis of a VRF and Mini Split system for the building complex.

Engineering Economic Analysis of the VRF and Mini Split systems.

2. Methodology

2.1 Site Survey and Environmental Parameters

The study building is the Olusegun Obasanjo Engineering Complex (Figure 1) in Ibogun campus, Olabisi Onabanjo University Ogun State, Nigeria on Longitude 3.4728610oE and Latitude 6.7003410^{o}N at about 39 meters above sea level, 50.2% - 94% relative humidity, and a dry season design temperature of 35^{o}C and a rainy season design temperature of 21^{o}C.

The Engineering complex consists of three departmental buildings, which are identical but vary with respect to orientation. Each building has 2 lecture halls, 2 laboratories, 1 seminar hall and 13 offices as shown in Figure 1.

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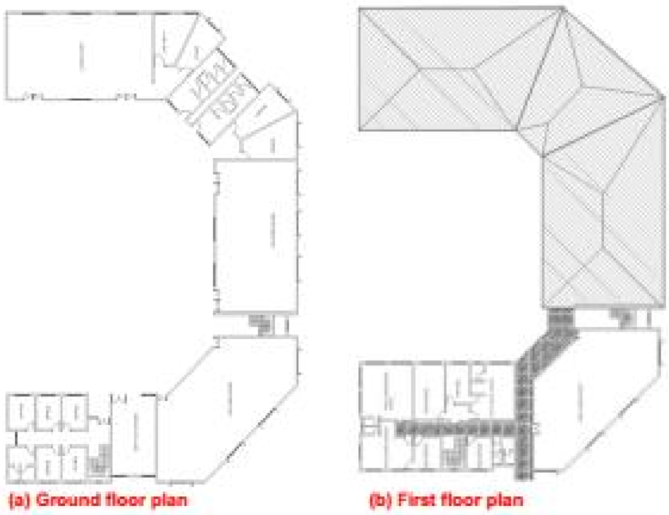

Figure 1. The Building Plan

The environmental data collected for the site are CO_2, particulate matters [PM2.5/ PM10) at different time of the day categorised into morning and afternoon, which helps to determine the number and spread of particulate matters and concentration of CO_2 present in study area. The design for ventilation and indoor air quality of the building complex depends on these information. The collected data was analysed to derive the minimum, maximum and average values of each parameter collected.

2.2 Space Audit/ Cooling Load Estimation

The air conditioning load was estimated to provide the basis for selecting the most suitable air conditioning equipment for offsetting the estimated load. The load estimate took into consideration the 'heat gains' into the space from outdoors on a design day as well as the heat being generated within the space.

In this context, design day is referred to:

A day on which the dry band wet bulb temperatures are peaking simultaneously resulting in high relative humidity.

A day on which there is little or no haze in the air to reduce solar heat gains.

A day on which all the internal loads are at their peak.

For the study, a computer simulation software (Carrier Hourly Analysis Program) was used for estimating the weather data for a period of one year. After which, the design day was gotten and was used as basis for the cooling load estimation.

2.3 Comparative Analysis of the Two Alternate Systems

2.3.1 Variable Refrigerant Flow (VRF) System

VRF systems are improved versions of multi-split systems (Figure 2), allowing more indoor units to be connected to an outdoor unit, with extra features such as simultaneous heating and cooling and heat recovery. The outdoor unit contains one or more variable speed compressors, condenser, accumulator, receiver, expansion device and controls. The outdoor unit is connected via a single flow and return refrigerant pipe-work system to a number of indoor units containing a fan, evaporator, expansion device and controls. A VRF system contains at least two indoor units (a system can extend to 64 indoor units) and one outdoor unit and a central controller. All the indoor and outdoor units are connected via an electronic system controlled by software-based systems within the outdoor unit. The indoor units are controlled either individually or in zones. [Goetzler (2007)].

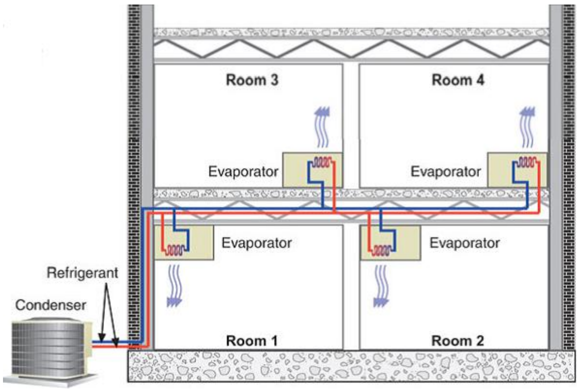

Figure 2. VRF System [Source: Amarnath and Blatt, (2008)]

2.3.2 Mini Split Air-conditioning System

A mini split air conditioning system (Figure 3) comprises of an outdoor condensing unit containing a constant speed compressor, a condenser, a receiver, a fan, and controls linked via a liquid and gas refrigerant pipe-work to the indoor unit containing the fan, the cooling coil, the thermostatic expansion valve and controls.

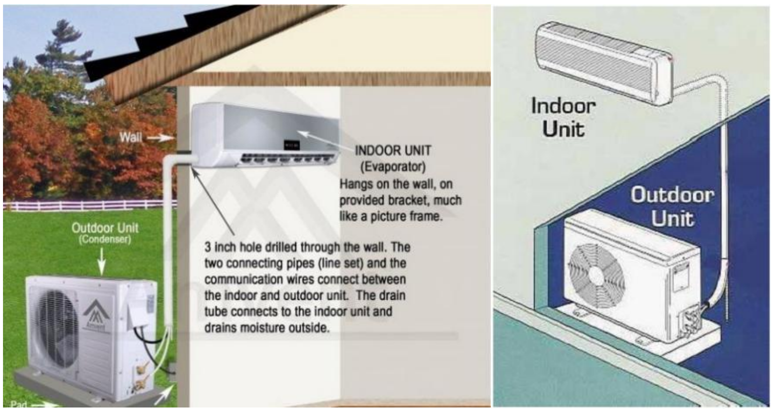

Figure 3. Mini Split System [Source: Brar, (2012)]

2.3.3 Design Analysis

Both the VRF and mini split air conditioning systems are direct expansion systems, therefore the procedure for the design analysis of the two systems followed the same trend. The procedures for accomplishing the design analysis of the two systems includes:

Building survey: Architectural drawings and field sketches [OOU, (2006)] were taken for the building survey and the following physical aspects were considered: Building Orientation, Compass Points, nearby permanent structures, reflective surfaces, use of spaces, physical dimensions of the spaces, construction materials (for walls, windows, roof, doors & partitions), surrounding conditions, occupancy levels and activities, lighting, appliances and thermal storage.

Location of Equipment and Services:

Air Conditioning Load Estimate: The air conditioning load was estimated to provide the basis for selecting the most suitable air conditioning equipment for offsetting the estimated load. Carrier

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hourly analysis program [Carrier (2011)] was used for estimating the air conditioning loads for the various spaces in the building. The software (hourly analysis program for detailed cooling load calculation) utilises the ASHRAE Transfer Function Method (TFM) of cooling load calculation for estimating the heat gains from walls and roofs, windows, doors, floors, lighting, equipment, people and infiltration sources [ASHRAE (1992), ANSI/ASHRAE (2004)].

Figure 4. VRF System Divisions: Ground Floor (a and b), and First Floor (c)

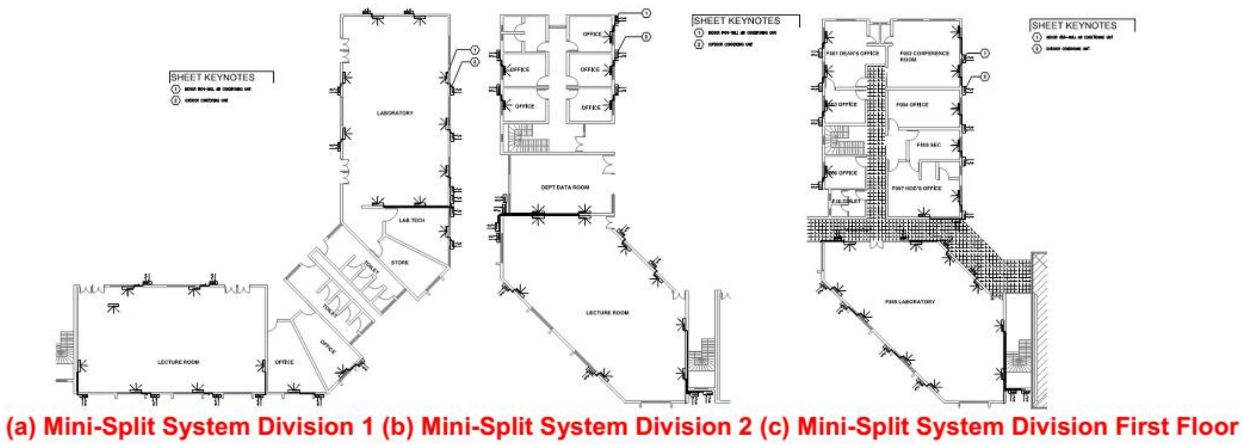

Figure 5. Mini-Split System Divisions: Ground Floor (a and b), and First Floor (c)

With the Transfer Function Method applied in the study to determine the cooling load of the building complex, a general mathematical model, which defines load as a function of heat gain and time was determined for each heat gain component in the rooms. This relationship was then used to calculate loads for each hour in the rooms. The mathematical model used expresses the Room Transfer Function [HAP (2016)] equation (1) as:

$$Qo = v_0 q_0 + v_1 q_1 + v_2 q_2 - w_1 Q_1 - w_2 Q_2 \quad (1)$$

In this equation:

Q_0 represents a load. The subscripts refer to specific points in time. Subscript 0 is the current hour, 1 is the previous hour and 2 is two hours previous.

q represents a heat gain. The subscripts 0, 1 and 2 have the same meaning as for loads. V_0, v_1, v_2, w_1 and w_2 are transfer function coefficients. Values of these coefficients vary for each type of heat gain and room due to the different heat transfer processes involved in converting each kind of heat gain into a load.

The Room Transfer Function Equation relates the load for the current hour (Qo) as a function of the heat gain for the current and preceding two hours, plus the loads for the preceding two hours. Because loads for the preceding two hours are themselves dependent on a series of heat gains for prior hours, the present hour's load is very dependent on the effects of heat gains from many preceding hours.

Detailed simulations resulted in generation of both sensible and latent loads for each of the spaces, which were further used for the selection of the appropriate HVAC equipment, for the two alternate systems. Catalogues were used for selecting the equipment for the mini split air conditioning system, while Toshiba SMMS-SHRM selection module was used for selecting the equipment for the VRF air conditioning system. Detailed layout of both systems indicated that the VRF system required only four outdoor units to provide thermal comfort for the spaces served by the individual indoor units (Figure 4), while the mini-split system requires as much outdoor units as the number of indoor units to provide thermal comfort for each of the spaces as shown in Figure 5.

2.4 Engineering Economic Analysis (EEA)

To select the economically sound option between the VRF and the Mini-Split systems designed for the building, an Engineering Economic Analysis was carried out using the net present worth analysis for both systems [Brar, (2012)]. In the EEA, the following costs were taken into consideration and converted into the net present worth values for proper comparisons;

First Cost: This refers to the cost of purchasing the equipment and installing the systems i.e. all the units and piping networks.

Annual Maintenance Cost: This refers to the cost necessary to maintain the systems on an annual basis.

Annual Energy Cost: This refers to the electrical energy cost necessary to run the Air-Conditioning systems on an annual basis. This was based on 9 hours of equipment usage on a daily basis, and 5 days on a weekly basis. The total kWhr of energy usage for both systems were computed using the electrical energy capacities of the A/C equipment selected.

The net present worth values of the various future cost components was computed as a function of the future cost, the interest rate, number of years and the annual cost, equations (2) and (3) [Newnan *et. al.*, (2004)]. An interest rate of 12% based on CBN 10-year average inflation rate [CBN (2018)] was used for the computation.

$$P = F\ (P/F,\ i\%,\ n) = P = F(1 + i)\text{-}n \qquad (2)$$

$$\&\ P = A\ (P/A,\ i\%,\ n) = A\left[\frac{(1+i)^n-1}{i(1+i)^n}\right] \qquad (3)$$

Where,

P = Present Worth of estimated future cost

F = Estimated future cost

I% = Interest rate

N = Number of years

A = Estimated annual cost

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3. Results and Discussion

Environmental Conditions

The environmental conditions as revealed in Table 1 show that the particulate matter PM 10 and CO2 are within the ASHRAE standards. This implies that no critical ventilation and air filtration systems are required in the design of the air conditioning system for the building complex.

Table 1. Average Values of the Environmental Conditions of the Study Area

	Morning		Afternoon		
	Maximum	Minimum	Maximum	Minimum	ASHRAE Standard
PM10 μg/m^3	35	20	33	14	50
CO_2 (PPM)	840	730	1000	701	350 – 1,000

Cooling Load Estimation

Table 2. Sensible and Latent Cooling Loads for Various Zones

ZONE	ZONE LOAD Sensible (W)	Latent (W)
F001 (Dean's Office)	6996	1480
F002 (Conference Room)	10021	2617
F003 (OFFICE)	3151	789
F004 (OFFICE)	4779	1330
F005 (SECRETARY'S OFFICE)	3127	847
F006 (OFFICE)	3322	762
F007 (HOD'S OFFICE)	5559	1620
F008 (LAB)	14379	4972
F009 (LAB)	15484	5642
G001 (LAB)	14699	2787
G002 (LAB)	21235	4178
G003(LAB TECH)	5042	672
G004 (OFFICE)	4148	636
G005 (OFFICE)	4571	606
G006 (LR)	15791	3234
G007 (LR)	14063	2874
G008 (LR)	14767	3451
G009 (LR)	15422	3574
G10 (DDT)	6765	1290
G11 (OFFICE)	2092	449
G12 (OFFICE)	2057	449
G13 (OFFICE)	2092	449
G14 (OFFICE)	1754	451
G15 (OFFICE)	2317	451
TOTAL COOLING LOAD (W)	193,633	45,610

Based on the design analysis carried out, the total design cooling load for the building complex was 239.2 kW, with 193.6 kW as sensible heat and 45.6 kW as latent heat as shown in Table 2. The design layouts (Figures 4 and 5) indicate that the VRF system requires only four outdoor condensing units to serve all the indoor air conditioning units in the building. This system hence aesthetically improves the look of the building which is a major architectural consideration, while the mini-split system requires a single space for each of the outdoor units which definitely requires an angle iron bracket or a condensing unit shelter for each of the outdoor units which becomes an extra consideration by the structural engineer and definitely comes with a cost implication. The mini-split system, which requires more components and invariably higher initial cost, has gains in annual maintenance cost (N1.6 million) in comparison with the VRF system's annual maintenance cost (N4 million) as shown in Table 3. However, due to the newness of the VRF system, the initial cost is higher than that of the mini-split as also noted by William, (2007), which will reduce in time as the technology becomes widely used. In terms of flexibility in operations and control the mini-split is found to be more flexible and cost saving in operation as many units can be switched off at a time without each unit affecting other units, this is in agreement with the report of STR partners and CS2 Design group (2013).While for the VRF system in which an outdoor unit controls two or more indoor units, if one or more of the indoor unit is switched off and only one indoor unit is in operation, the outdoor unit continue to operate. And in the event the outdoor unit becomes faulty, all the indoor units attached to it will become inoperative.

Table 3. A breakdown of the various cost components as used for analysis of both systems

Cost	VRF System	Mini Split System
First Cost	N29.5 Million	N22 Million
Annual Maintenance Cost	N4 Million	N1.6 Million
Annual Energy Cost	N2.5 Million	N2 Million
Total Cost	N36 Million	N25.6 Million

Table 4. A breakdown of the various cost components converted to net present worth

Cost	VRF System	Mini Split System
First Cost	N29.5 Million	N22 Million
Annual Maintenance Cost converted to the Net Present Worth	N30 Million	N11 Million
Annual Energy Cost converted to the Net Present Worth	N17.5 Million	N13 Million
Net Present Worth	N77 Million	N46 Million

Based on the Engineering Economic Analysis carried out on the two systems, the overall Net Present Value for the VRF system is N77 million , while that of the Mini-Split system is N46 million as shown in You started your methodology with systems analysis and began your results and discussion with costs. This is unacceptable and unpublishable. You must reorganize and revise your paper appropriately.

Table 4. This result shows that the VRF system has a higher cost implication than the mini-split system. Hence, in terms of cost, the mini-split system is a more viable option.

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However, it should be noted that a number of parameters were left out of consideration during the analysis. Of utmost importance is the annual energy estimation of the VRF system at part load operation which requires a detailed simulation of the electrical energy consumption with respect to the cooling load at different points in time. This simulation would have resulted in a lesser value for the electrical energy consumption as compared to the actually estimated value.

From Figure 6, it is observed that the initial cost of the two systems are close. However, using a 15% of initial cost as annual maintenance cost builds up the maintenance cost of the VRF system over the period of time used for the analysis. The difference in the initial cost of the two systems is due largely to the newness of the VRF into the market. With time the VRF system is bound to cost less than the mini-split system as demand for the product increases.

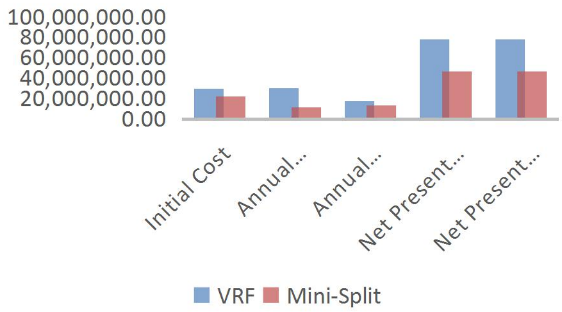

Figure 6. Comparative cost analysis of VRF and mini-split systems.

Also as noted, the analysis of cost is based on full-load, where all the units are working at maximum capacity. However, under part-load conditions the gains of the VRF systems will be obvious. Gains such as the lower energy consumption of the outdoor unit under part-load conditions, which may bring the energy cost of the VRF system lower than that of the mini-split since most of the energy demand of the VRF is for the outdoor unit. This is due to the presence of multiple compressor and variable speed compressor that enable good part load performance permitting capacity modulation to serve 7% to 100% of the cooling or heating loads. Furthermore, the efficiency of the systems were not considered in the analysis, which will affect the performance and the energy cost over the duration of usage. The HVAC systems operation's daily time period has between 30% and 70% of the system working on maximum capacity where the VRF system efficiency is high.

Another energy gain of the VRF system has to do with its abilities to provide good zone control, saving energy and cost by not conditioning zones that are unoccupied and also providing capability to condition single zones off hours at a reasonable cost.

4. Conclusion

The set objective of the research, which was to design an energy efficient, cost effective and environmentally friendly air-conditioning and ventilation system for the engineering complex building at the College of Engineering and Environmental Studies, Ibogun Campus, Olabisi Onabanjo University, was achieved. Environmental data taken at the initiation of the study showed that the average value of the ambient CO_2 was within the internationally acceptable standard, and thus not critical ventilation system required. The total cooling load estimation of the building complex was 193.6 and 45.6 kW for sensible and latent cooling loads respectively. Technical and performance characteristics indicated that the variable refrigerant flow system is a better air-conditioning option, with fewer components and a centralised system, than the mini-split air-conditioning system with many more components and a decentralised control system. However, the economic analysis carried out favoured the mini-split air-conditioning system with a net present worth of N46 million over of the VRF system with a net present worth of N77 million. To come up with a more detailed engineering economic analysis of both systems, a further research would be necessary for the estimation of the actual energy consumption of both systems as this would result in a more concise figure for the systems since energy cost is a major consideration during the actual running of the systems.

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