Study on Variable Refrigerant Volume Air-conditioning System

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Declaration

I hereby declare that this submission is my own work and that, to the best of my knowledge and behalf, it contains no material previously published or written by another person nor material which to substantial extent, has been accepted for the award of any other academic qualification of a university or other institute of higher learning except where acknowledgment is made in the text

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Abbreviations

CBSL - Central Bank of Sri Lanka

CLF - Cooling Load Factor

COP - Coefficient of Performance

DEC - Direct Evaporative Cooling

DX - Direct Expansion

EER - Energy Efficiency Ratio

EEV - Electronic Expansion Value

FPFA - Fan-Coil Plus Fresh Air

IGH - Internal Heat Gain

LCC - Life Cycle Cost

OAC - Overall Average Annual Cost

VRF - Variable Refrigerant flow

VRV - Variable Refrigerant Volume

Abstract

During the last two decades, air-conditioning has become a basic requirement in industrial, commercial and residential sectors. With the widened use of air-conditioning in all the sectors, the human community has faced serious environmental and socio economic problems. Prevailing energy crisis and ever increasing energy pieces has made the situation worst. Under the scenario, various novel technologies have been emerged to the air-conditioner market. Variable Refrigerant Volume (VRV) air-conditioning technology is also considered as an advanced technology developed to cater the need of efficient use of energy for air-conditioning.

The major objective of the research study was to analyze the suitability of VRV air-conditioning system, analyze the actual saving potential and cost effectiveness of VRV air-conditioning system compared to the other available types of air-conditioning systems and access the maintainability of VRV air-conditioning system. The study was conducted at a selected representative installation namely at the Sovereign Residences of Central Bank of Sri Lanka. Summary of findings are as follows,

- VRV air-conditioners are suitable for medium scale hotel applications. However, this conclusion cannot be generalized for all the installations and the appropriate air-conditioning system for particular building should be selected only after performing a comprehensive analysis of energy performance of considered options on that particular installation (preferably after a computer simulation and life cycle cost analysis of different options). Therefore, though the demand for VRV air-conditioning system is prevailing due to the higher efficiency rating and the part load performance of the air-conditioning appliances, the desires of the purchases on energy saving potential of VRV air-conditioners could be satisfied only when it is selected for an appropriate application.
- Saving potential of VRV air conditioners could be high as 18 % compared to the energy consumed by split air-conditioning systems when used for appropriate applications. Therefore, the VRV system can be considered as a potential candidate for the installations where the building occupancy and cooling load are regularly varying. Further, Chiller (Central) air-conditioning system can also be considered as a potential candidate as it performs almost efficiently as the VRV system. It consumes around 4 % more energy than VRV system.

- Computer simulation (Equest) shown that VRV air-conditioning system is the most efficient option among the potentially applicable options considered for the building. However, the Life Cycle Cost (LCC) analysis shows that Chiller system is the most economical air-conditioning system for the same building. Therefore, it is vital to perform LCC analysis in addition to performance analysis when selecting the appropriate air-conditioning system for a building.
- Maintainability of the VRV air-conditioning systems is acceptable. It is necessary to select the correct density and thickness of the refrigerant pipe insulation to minimize the possibilities of formation of condensation along the refrigerant pipes. Also, the power quality should be maintained at an acceptable level to ensure the durability and proper functionality of electronics of the VRV air conditioning equipment.

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CHAPTER 01

Introduction

1 Introduction

1.1 Background

A decade back, air-conditioning was considered as a luxury facility. It was available in Luxury residences, luxury hotels, luxury office rooms and processing/manufacturing plants where the air-conditioning is essential for the process. But, within a short period, air-conditioning has become a basic requirement in all the sectors. It is no longer considered as a luxury facility. At present, most of the commercial buildings, hotels, processing/manufacturing plants and considerable number of residences are fully air-conditioned.

With the widened use of air-conditioning in all the sectors, the human community has faced serious environmental and socio economic problems. Air-conditioning is an energy intensive process. When compared with the other energy users buildings it dominates with a high difference. Though there may be few energy users in processing/manufacturing plants which consume energy in a similar order, air-conditioning takes the lead in the energy use in all other commercial and industrial buildings. Therefore, air-conditioning has become a huge burden to the relevant sectors and a severe threat to the environment and human community.

Under this scenario, two new major needs have been arisen in the organizations. One need is to maintain the financial stability of the organization in order to be competitive in the market despite of the high cost incurred by the operation of air-conditioning systems. The second need is to comply with the national regulations, requirements and aiming at the building certification systems in respect of energy conservation and environmental protection in order to secure the corporate image of the organization.

Catering these two needs is of two fold. Providing energy and environmental expert services in the form of consultation, auditing and certification is one part. Developing the energy efficient air-conditioning systems and equipment which could improve the energy efficiency and environmental friendliness to make the installation comply with the regulations whilst supporting the burden of high energy bills is the other part. The latter need has created a huge market demand for the energy efficient air-conditioning equipment and thereby a widen opportunity for the manufacturers and dealers of air-conditioning equipment. Variable Refrigerant Volume (VRV) air-conditioning technology is also considered as an advanced technology developed to cater the above requirements.

1.2 Problem statement

Energy efficient and environmentally friendly air-conditioning equipment/systems are a highly technical need, which is felt by non-technical entrepreneurs. As these entrepreneurs do not possess the expertise and knowledge on the air conditioning techniques, the selection of appropriate option or technology does not evident in most instances. With the intensive promotion campaigns conducted by the air-conditioning dealers regarding the new technologies available with their air-conditioning systems and the benefits of those technologies, the users get rather confused. In most of the instances, they acquire most promoted or advanced air-conditioning appliances like VRV systems which have developed to cater a specific application which may not be appropriated for intended application. This is a very complicated and serious problem.

1.3 Objectives of the project

Under the above scenario, it is essentially required to perform a comprehensive study on the VRV technology. The objectives of this research project are to,

- Understand whether the prevailing demand for VRV air-conditioners is really because of its ability to cater the desires of purchases and users.
- Estimate the saving potential of VRV air-conditioners compared with the other available potentially applicable air-conditioning systems for the building and financial analysis of those systems.
- Study the maintainability of VRV air-conditioning installations based on the information collected from the Owner / Maintenance Manager of an identified representative building where a VRV air conditioning system has been installed.

1.4 Methodology followed for the study

Methodology followed to study the maintainability, saving potential, desired application and suitability of VRV air-conditioning systems is of two fold. In the first approach, research study was conducted mainly on theoretical basis. Therefore, the study was started from the thorough study on the air-conditioning principles and VRV technology. Accordingly, the basic principles of air-conditioning and theory behind the VRV technology were studied in detail. Key components of the system, their functionality and their effects on the performance of VRV air-conditioning system were also studied.

Then, the behavior of VRV air-conditioning systems on different types of buildings with different occupancy and operational patterns were analyzed. After studying the behavior and performances of VRV air-conditioning system on different applications, their performances were compared with the performance of other available air-conditioning systems on the respective applications. By this comparison, the most suitable technology for each application was identified. The first approach, which is a theoretical analysis of relevant literatures substantially confines to the literature review.

In the second approach, some buildings where large scale VRV air-conditioning systems have been installed were selected and the systems were studied thoroughly. Originally, it was planned to conduct an opinion survey on the suitability of VRV air-conditioning system for different types of buildings by means of a questionnaire. It was also planned to send this questionnaires to three types of stakeholders (experts and professionals practicing in the field of air-conditioning, owners and maintenance managers/engineers of buildings where VRV air-conditioners are installed and air-conditioning contractors who have installed substantial number of VRV air-conditioning systems in Sri Lanka). It was intended to assess the maintainability, saving potential, desired application of VRV air-conditioning system and suitability of it for the buildings in Sri Lanka by studying the responses furnished in the questionnaires. But it has been reported that most of the researchers who conducted this type of surveys to gather highly technical information for their research projects had expressed their dissatisfaction about the responses they had received for their questionnaires.

Due to this practical problem, it was decided to select a representative VRV air-conditioning installation and to carry out a comprehensive study on the following areas to achieve the research objectives listed in 1.4.

- Factors considered by the designers, project team and owners in selecting the VRV air-conditioning system for the building.
- Maintainability of the system and problems encountered by the owners of the building with regard to the maintenance of the air-conditioning system.
- Energy efficiency of the VRV air-conditioning system and its saving potential and whether the expected benefits have been gained by the building owners.

- Whether the suppliers/contractors have maintained the system to the satisfaction of building owners
- Whether the VRV technology is suitable for the building
- Whether the VRV system is financially viable

After, analyzing the above factors on the selected VRV air-conditioning installations, conclusions were made considering the theoretical and practical aspects.

1.5 Significance of the study, scope and limitations

As the VRV technology is an emerging technology, the advantages and disadvantages of the VRV air-conditioners are not established well. Therefore, comprehensive study on VRV technology and VRV air-conditioners is essentially helpful to identify the special features, technical advancements, superiorities, advantages and limitations. As the demand for VRV air-conditioners has shown an increasing trend, it is vital to analyze the VRV technology. Purchasers have lot of expectations on the benefits of VRV air-conditioners as it is believed that VRV technology is a very advanced and novel technology which can offer outstanding energy efficiency and more than desired performance level. The purchasers of VRV air-conditioners see only the promotions and claims made by the suppliers and manufacturers of those equipment. They don't get the real feedback from the owners and facilities managers of the buildings where VRV air-conditioners are installed. As there are only a few VRV installations in Sri Lanka, and those systems have been installed in the recent past, maintainability of the system is not known to the majority of interested and involved parties. Further, the operation and maintenance manuals provided by the manufacturers of the equipment do not ensure the practical aspects of the maintainability.

Therefore, analyzing the actual saving potential of VRV air-conditioners in different applications is helpful to users /purchasers in making informative purchase decisions with regard to the appropriate technology for respective installations. It also establishes a basis for justifying the additional investment involved with the selection of VRV air-conditioning system. As the VRV air conditioners have no long maintenance history, it is vital to study and analyze the maintenance experience of present users of VRV air conditioners to improve the maintainability of future VRV installations. It will be also possible to identify the most suitable installation method for different applications. Suitable applications of VRV technology will be explored by means of technical analysis, energy performance and installation methodology. This will look into the technical suitability of VRV technology for different applications, its energy performance under different climatic conditions and operating conditions. In addition, the installation convenience of VRV technology for different site conditions will also be studied.

Though there are few studies carried out on the energy efficiency of VRV air-conditioners, it is hard to find comprehensive studies which also look in to the overall aspects such as the maintainability, installation convenience and satisfying the purchaser expectations. Therefore, purchasers are unable to make informative purchase decisions. By carrying out this study, lot of information will be made available to the purchases to make smart and informative purchase decisions. Therefore, this study aims to reveal a lot of vital information on the VRV air-conditioners which will be really useful for the stakeholders.

The scope of this study will be confined to the commercial buildings as the VRV air-conditioners are largely installed in commercial buildings [1], [2]

1.6 Influence of building certification systems on air-conditioning industry

As revealed in the above section, the building certification systems were evolved with the growing concern of sustainable development and environmental conservation. Global energy crisis and rapid environmental degradation were among the major motive factors which influenced the environmentalist and designers to think and commit on the sustainable development. Further, they recognized green building certification concept as a tool to achieve the sustainability. Most of the green building certification systems have given a high weighting on the indoor air quality and thermal comfort in the buildings.

With the high emphasis given to the attributes related to the air-conditioning by the green rating systems, a huge demand has been created for the efficient air-conditioning appliances and systems. This market trends has motivated the manufacturers to improve the efficiency of their appliances and air-conditioning systems. The manufacturers of air-conditioners have given a high priority for the research and development to improve the technology of their air-conditioners, correctly identifying the market trends and market competition. Under the scenario, air-conditioning technology has undergone a rapid advancement during the last decade. Over the time period, the manufacturers have realized that the purchasers becoming knowledgeable on the performance characteristics of the appliances. As a result, due prominence and funding were secured to improve the technology towards the high performance and efficiency. Only the Air-conditioning manufacturers who introducing technological improvements frequently were able to survive in the market and to secure their market share.

With the identification of air-conditioning as a main culprit of energy and environmental crisis, energy and environmental specialists emphasized the need of establishing the strong regulatory arm to curtail the existence of low efficient appliances in the market. Importance of controlling the production of appliances which directly or indirectly contribute to the environmental pollution was also identified by the authorities. Accordingly, in most of the countries, regulatory authorities were formed to regulate the energy and environmental aspect of appliances. Most of these regulatory bodies have mandated the availability of performance characteristics of appliances with the appliance when it is coming to the market. With time, the minimum performance levels were introduced by the regulators to eliminate the inferior quality and low efficient appliances in the market.

1.7 Summary of the Results of the research project and recommendations

From the research study, it was concluded that,

1. The design and project teams of the selected installation (i.e. The project team of Center for Banking Studies) have considered the following factors when selecting the appropriate air-conditioning system for the project.

- Suitability of the proposed air-conditioning system for the building.
- Installation convenience and space available for the installation of air-conditioning system, pipes, and equipment.
- The impact of equipment installed outside the building on the external appearance of the building.
- Maintainability of the different systems considered for the installation.
- Energy efficiency of different feasible options.

2. There had been some maintenance problems during the initial period of operation. The major problem was the weakening of the insulation of refrigerant pipes and leaking of refrigerant through the refrigerant pipe network. After rectifying these problems several times, the system has been operated satisfactorily without major

failures. Hence, there were no major concerns regarding the maintainability of the VRV air-conditioning system.

3. The contractor who installed the VRV air-conditioning system had attended on the technical faults of the system satisfactorily. The capability of the technical team of the contractor on trouble shooting and maintenance of VRV system is satisfactory.
4. The outcome of the simulation has revealed that the overall energy performance of these systems does not exclusively depend on the rated energy efficiencies. According to the simulation, the best energy performance has been resulted from VRV air conditioning system and Chiller system also shown almost similar performance. The annual energy consumption of VRV, Chiller and Split type air-conditioners are 310.41 MW, 322.18 MW and 367.01 MW respectively. However, Life Cycle cost analysis has shown that the most economical system for the building under study is chiller system which is not the most efficiently performing system for the same building. According to the life cycle cost analysis, the overall average annual cost of chiller, VRV and Split air-conditioning systems are Rs. 9,109,604.00, Rs. 9,604,220.00 and Rs. 10,097,420.00 respectively.

   Performance of any air-conditioning system at a particular building depends on the building architecture, occupation pattern and activities performed in the building. Therefore, the appropriate air-conditioning system for particular building should be selected only after performing a comprehensive analysis of energy performance of considered options on that particular installation (preferably after a computer simulation and life cycle costing of different options). Therefore, though the demand for VRV air-conditioning system is prevailing due to the higher efficiency rating and the part load performance of the air-conditioning appliances, the desires of the purchases on energy saving potential is satisfied only when it is selected for an appropriate application.
5. Energy saving potential of VRV and Chiller air conditioning systems with respect to a building of similar nature, could be around 18.2% and 13.9% compared to the energy consumption of split type air-conditioning systems respectively. VRV system is preferred for the installations where the building occupancy is regularly varying.

CHAPTER 02

Literature Review

2 Literature Review

2.1 World scenario of usage of air-conditioners

During the last decade, the need for cooling of buildings has increased. A 30% increase in worldwide sold air conditioners had been reported from 2000 to 2004 and expected to increase by the same percentage within another two years period (i.e. From 2004 to 2008) [3]. The main drawback of the air-conditioning systems is their large energy usage and their contribution to the emission of greenhouse gases. As a result of the booming market for air conditioning, the emission of greenhouse gases has increased and the global warming has shown an accelerating trend. World sales of air-conditioning in 2011 were up by 13 percent over 2010, and that growth is expected to accelerate in coming decades. According to the predictions by energy researches, worldwide residential, commercial, and industrial air conditioners consume at least one trillion kilowatt-hours of electricity annually. They have predicted that it is possible that world consumption of energy for cooling could explode ten times by 2050 if the present trend is prevailed.

The United States had consumed more energy each year for air conditioning than the rest of the world combined. In fact, they used more electricity for cooling than the entire continent of Africa, home to a billion people, consumes for all purposes. Between 1993 and 2005, energy consumed by residential air conditioning in the U.S. doubled, and it leaped another 20 percent by 2010. Energy specialists have indicated that China is expected to surpass the U.S. as the world's biggest user of electricity for air conditioning by 2020.

The time window for debating the benefits and costs of air conditioning on a global scale is narrowing. Once a country goes down the air-conditioned path, it is very hard to change the course. China is already sprinting forward in use of air-conditioning. It has been reported that the number of U.S. homes equipped with air conditioning rose from 64 to 100 million between 1993 and 2009, whereas 50 million air-conditioning units were sold in China in 2010 alone.

As urban areas of China, Japan, and South Korea approach the air-conditioning saturation point, the greatest demand growth in 2020 is expected to occur elsewhere in the world, most prominently in South and Southeast Asia. India has shown that they are going to predominate the demand for air-conditioners and even at present, about 40 percent of all electricity consumption in the city of Mumbai goes for air conditioning [4]. The Middle East is already heavily climate-controlled, but growth is expected to continue there as well. Within 15 years, Saudi Arabia could actually be consuming more oil than it exports, due largely to air conditioning [5]. Most of the Asian countries are already struggling to keep up with peak power demand against the increasing use of appliances like air-conditioners which accounts for increasing demand of energy. India is experiencing a shortfall of generation capacity to meet the demand and, sometimes interrupt the electricity supply for residential sector for 16 hours per day in some areas whereas China is experiencing a short of around 30 to 40 GW, resulting in energy rationing and factory closings. Despite the circumstance, countries like United States and Mexico continue increasing their heavy consumption of air-conditioning.

Based on projected increases in population, income, and temperatures around the world, Morna Isaac and Detlef van Vuuren of the Netherlands Environmental Assessment Agency predict that in a warming world, the increase in emissions from air conditioning will be faster than the decline in emissions from heating; as a result, the combined greenhouse impact of heating and cooling will begin rising soon after 2020 and then shoot up fast through the end of the century [6]. In a reference scenario, global energy demand for heating is projected to increase until 2030 and then stabilize. In contrast, energy demand for air conditioning is projected to increase rapidly over the whole 21st century, mostly driven by income growth. The associated CO_2 emissions for both heating and cooling increase from about 12% of total CO_2 emissions from energy use (the strongest increase occurs in Asia). The net effect of climate change on global energy use and emissions is relatively small as decreases in heating are compensated for by increases in cooling. However, impacts on heating and cooling individually are considerable in this scenario, with heating energy demand decreased by 34% worldwide by 2100 as a result of climate change, and air-conditioning energy demand increased by 72%. At the regional scale considerable impacts can be seen, particularly in South Asia, where energy demand for residential air conditioning could increase by around 50% due to climate change, compared with the situation without climate change.

2.2 Advancement of air-conditioning systems

2.2.1 Usage of various air-conditioning systems and technologies in Sri Lanka

The primary function of all air-conditioning systems is to provide thermal comfort for building occupants. There are a wide range of air conditioning systems available, starting from the basic window-fitted units to the small split systems, to the medium scale package units, to the large chilled water systems, and currently to the variable refrigerant volume (VRV) systems. However, the following classification is being used most commonly in the industry based on the operation principle, usage, and method of assembly of the air conditioners.

- Unitary Air-conditioners
- Split air conditioner
- Package Air-conditioners
- Central Air-conditioners

Unitary air-conditioners: From the above, unitary air-conditioners are most commonly used by the domestic and small commercial sectors for domestic and commercial installations. Unitary air conditioning units can be further classified into two different categories namely window and split air conditioners. Window air conditioner was the most commonly used air conditioner for single rooms few years back. In this air conditioner all the components, namely the compressor, condenser, expansion valve or coil, evaporator and cooling coil are enclosed in a single box. This unit is fitted in a slot made in the wall of the room, or often a window sill.

Split air conditioner: It comprises of two parts; the outdoor unit and the indoor unit. The outdoor unit, fitted outside the room, houses components like the compressor, condenser and expansion valve. The indoor unit comprises the evaporator or cooling coil and the cooling fan. For this unit you don't have to make any slot in the wall of the room. Further, the present day split units have aesthetic looks and add to the beauty of the room. The split air conditioner can be used to cool one or two rooms. The split type air-conditioners, when confederated with more than one indoor unit, are known as multi-split air-conditioners. Multi-split air-conditioners have further been developed to cater different zones with varying loads by modulating the refrigerant floor based on the cooling demand in respective zone. As the capacity is controlled by varying the refrigerant flow rate to each indoor unit, the system is known as Variable Refrigerant Volume (VRV) system. It has the attributes of a central air-conditioning system also.

Packaged air conditioner: An HVAC designer will suggest this type of air conditioner if you want to cool more than two rooms or a larger space at your home or office. There are two possible arrangements with the package unit. In the first one, all the components, namely the compressor, condenser (which can be air cooled or water cooled), expansion valve and evaporator are housed in a single box. The cooled air is thrown by the high capacity blower, and it flows through the ducts laid through various rooms. In the second arrangement, the compressor and condenser are housed in one casing. The compressed gas passes through individual units, comprised of the expansion valve and cooling coil, located in various rooms.

Central air conditioning system: The central air conditioning system is used for cooling big buildings, houses, offices, entire hotels, gyms, movie theaters, factories etc. If the whole building is to be air conditioned, HVAC engineers find that putting individual units in each of the rooms is very expensive initially as well in the long run. The central air conditioning system is comprised of a huge compressor that has the capacity to produce hundreds of tons of air conditioning. Cooling big halls, malls, huge spaces, galleries etc is usually only feasible with central conditioning units.

2.3 Appropriate technologies

With the trend of sustainability and been green, the designers started to insist on efficient appliances, systems and passive techniques. Due to the high prominence given for the indoor air quality and thermal comfort in the green rating systems, more emphasis was given to the efficient and passive air-conditioning techniques by the designers in light of achieving a better green rating for buildings. Concurrently the interest of Green Building Designers was mainly forced on following HVAC technologies in the process of complying with the Green Rating system.

2.3.1 Evaporative cooling technology

Evaporative cooling is a passive technique in which the dry bulb temperature of air is lowered by evaporation of water. Two types of evaporative cooling systems can be distinguished as direct and indirect evaporative cooling systems. In a direct evaporative cooling installation (DEC) the supply air to the building is humidified. In an indirect evaporative cooling system (IEC) a secondary air flow is cooled by adiabatic humidification using sprayed water. In an air to air heat exchanger this air cools down the supply air to the building. Fresh outdoor air or building return air can be used as secondary air. The advantage of indirect evaporative cooling is that in contrast to direct evaporative cooling, the vapor content of the supply air is not increased. This will lead to a more comfortable indoor climate and fewer moisture problems in the indoor environment are expected.

Indirect evaporative cooling performs best in dry hot areas but also has good potential in most locations with moderate humidity [7] as revealed by the analysis undertaken by M. Lazzarin. The analysis investigates the potential of direct and indirect evaporative cooling for different types of climates. An evaluation procedure is presented which shows that the cooling demand can often be satisfied completely combining direct and indirect evaporative cooling.

When return air is used as secondary air, water is evaporated and heat is withdrawn from the air due to latent heat transfer. As a result the return air is cooled. At the same time the supply air is cooled indirectly by sensible heat transport through the heat exchanger walls. The wet bulb temperature of the return air is a measure for the maximum vapor content of the return air at adiabatic saturation, which corresponds to the lowest possible temperature to which the return air may theoretically be cooled. The IEC-effectiveness can be defined by the ratio of the actual temperature reduction in the supply air realized by an IEC system to the maximum possible temperature change, which is given by the temperature difference between the dry bulb of the outdoor air and the wet bulb of the return air entering the heat exchanger [8].

Evaporative cooling has traditionally been most applicable to regions with a hot dry climate and as such these cooling systems are more typically associated with buildings in these regions. Work by Costello and Finn [9, 10], however, has shown potential for evaporative cooling systems in temperate regions also. The benefits of this cooling measure are most effective when applied to buildings requiring a relatively low mechanical air flow rate and comparatively high supply air temperature. These criteria are mostly applicable in building designs utilizing cooling methods such as chilled beams and displacement ventilation, particularly in mixed-mode buildings that utilize passive measures to minimize active cooling [10,11].

2.3.2 Variable refrigerant volume technology

VRV technology is also merging as a promising technology to achieve energy efficiency and better performance. The efficiency of the air-conditioning units is enhanced by introducing the inverter technology to the compressors and performance is enhanced by individual controlling of units. The VRV is considered to be the most energy efficient and most advanced technology for air-conditioning. It was first introduced in Japan more than 20 years ago. Today, the VRV systems account for about 99% of the residential segment and 60% of the commercial segment of Japan. As governments around the world set high standards on energy efficiency for A/C equipment and consumers become more aware of VRF as a technologically and aesthetically superior product, VRV has undoubtedly become the technology of choice. Many countries worldwide including China, South Korea, Australia, South East Asia, Europe, and USA are seeing VRV replace traditional splits and chillers in residential, industrial, and commercial establishments.

With forthcoming major infrastructure investments in India, the VRV air-conditioning market is growing at a fast pace. VRV systems with digital scroll compressors have rapidly gained acceptance and have been used in several major buildings. The popular applications for VRV A/C systems have been corporate offices, hotels, IT offices, high-end residential apartments and villas, retail stores, supermarkets and hospitals. The typical size of VRVs in India usually range from 300-400 HP, however, larger systems of 800 HP &1,000 HP are increasingly becoming popular. The ability of these systems to provide higher part load efficiency, potential considerations of diversity factor in typical applications to reduce the installed system capacity, simple system configuration that eliminates the need for operation & maintenance department staff, and great aesthetics, had major impact on the systems gaining popularity.

2.3.2.1 Basic principle of VRV technology

Variable refrigerant Volume (VRV) is an air-condition system configuration where there is one outdoor condensing unit and multiple indoor units. It is an advanced, highly technical and novel method of air-conditioning. The term variable refrigerant volume is also used for this technology and it refers to the ability of the system to control the amount of refrigerant flowing to the multiple evaporators (indoor units), enabling the use of many evaporators of differing capacities and configurations connected to a single condensing unit. The arrangement provides an individualized comfort control, and simultaneous heating and cooling in different zones.

With a higher efficiency and increased controllability, the VRV system can help achieving a sustainable design. Unfortunately, the design of VRV systems is more complicated and requires additional work compared to designing a conventional direct expansion (DX) system.

In VRV systems, number of indoor units are connected to a single outdoor unit or a bank of outdoor system consist of limited number of outdoor modules. For example, this type of system consists of a number of indoor units (up to 40) connected to one or more external condensing units. An expansion valve or control valve can modulate or stop the flow of refrigerant to each indoor unit, thus controlling its output to the room. The overall refrigerant flow is varied using either an inverter controlled variable speed compressor, or multiple compressors of varying capacity in response to changes in the cooling or heating requirement within the air conditioned space. A control system enables switching between the heating and cooling modes if necessary. In more sophisticated versions, the indoor units may operate in heating or cooling mode independently of others. An electrical inverter is used to vary the frequency of the power supply from a normal 50Hz enabling fine step speed control of motors (compressors) this in turn varies the flow rate of refrigerant delivered and hence varies the cooling or heating capacity of the indoor units. A Variable Refrigerant Volume (VRV) system has the advantage that it is energy efficient and flexible when compared to constant refrigeration flow systems. With the VRV technology, refrigeration pipework up to 300 meters long and level differences between indoor and outdoor units up to 50 meters are feasible. Usage of HFC refrigerants typically R-410-A and R-407-C is possible with the VRV air-conditioners. It has a wide capacity range and a higher COP.

2.3.2.2 Advantages and limitations of the VRV systems

Conventional air conditioners serve a building as a whole, whereas the VRV system air conditions serve each room individually. Hence it is ideal for the constantly changing occupancy of a typical building. Even further, precise temperature level control is possible that reacts to the exact conditions in each room. Individual control promotes a far more economical and efficient system. Few major advantages of VRV systems are as follows.

Greater energy saving potential: Generally, in a VRV system, large numbers of indoor units are connected to a single or few outdoor condensing units. All these individual indoor units which serve different rooms / zones have individual controls. These individual controls regulate the refrigerant flow through the evaporator and cater for the exact heat load in the room. Therefore, the refrigerant demand on the compressor at any instance will be the addition of instantaneous demands of each indoor units connected to that condensing unit. As this demand is a variable, the refrigerant flow rate of the compressor is regulated by an inverter (variable speed drive) by varying the frequency of the power supply. When compared with split, multi-split or package systems, VRV technology has a greater potential of saving energy due to the feature of individual controlling.

Conserves space: In many building projects, the designers of the services find difficulties to locate services. As the building space has a commercial value, architects allocated more spaces for rentable area and allocate only a very small and limited area for building services. Even where the architects are willing to allocate sufficient space for services, the developers and owners are reluctant to sacrifice substantial portion of the building area for building services. Under this scenario, there are projects where the building services engineer find difficult to allocate the required space for the different types of service appliances equipment. For example, space may not be available to install a package air-conditioners for a building for which the package type air-conditioning system is more desirable. In such situation, VRV system could be a more desirable option as it conserves the space. Significant amount of space can be saved by installing VRV systems as chilled water pipes, air ducts, air handling units, chilled water pumps and chillers are not essentially required for the VRV systems.

It saves energy, conserves space, Offers a wide selection of models, Operates over a broad temperature, and provides superior design flexibility, Enhances ease of use, delivers ultimate reliability, Simplifies installation.

2.4 Desired applications of VRV technology

As discussed above, VRV systems are capable of providing cooling on demand. They can cater different zones independently within the total capacity. Therefore, VRV system is a good candidate for installations which has variable cooling load. Variation of cooling load could be due to one or more from the following reasons.

- **Variation of external heat gain**

External heat gain is the heat flow to the building or zone through the building envelop. It depends on the overall heat transfer coefficient of the building envelop. But, for a given envelop, overall heat transfer is almost constant and the external heat gain substantially varies with the variation of outdoor conditions such as temperature, humidity, wind speed, wind direction, shading, solar radiation etc. This variation could be seasonal, hourly pattern (throughout the day), instantaneous or weather related. Though the seasonal climatic variations are not dominant in Sri Lanka, the daily and seasonal variation of solar radiation could make s significant variation of external heat gain depend on the building orientation. For example a long rectangular building oriented with it's longitudinal axis along the north / south direction experiences a considerable variation of external heat gain throughout the day whereas the same building if oriented in east – west direction would experience a seasonal variation of external heat gain.

- **Variation of internal heat gain**

The sources of internal heat gains include people (sensible and latent heat gain), lights (sensible heat gain only) and equipment. Equipment could be further classified as receptacles or electrical plug loads (sensible heat gain only) and Processes such as cooking (sensible and latent heat gain) Internal Heat Gain (IHG) can be a major component of the total building cooling load. This is particularly true of non-residential (commercial, institutional and industrial) buildings. HG for lights can be calculated if the type and number of lighting fixtures are known. This is also true for electrical equipment. IHG for people and process loads are approximate since the level of activity varies.

An IHG load for each hour of the year is estimated on the basis of percent of peak design load. Like the hourly weather data that affects energy loads due to the building envelope, infiltration and ventilation, internal loads can vary from hour to hour and year to year. A range of IHG design hour values from low, average and high can estimated on the basis of type of building. This is the type of information that is available. Such estimates apply to a particular region, country, economy and society. After the building is designed and built, it can be under-used or over-used. The building can be used for purposes other than what it was designed for. In the case of office buildings, lighting loads have decreased due to more efficient lighting and equipment loads have increased due to computers and telecommunication equipment.

In the case of under-usage, building's control system will adjust the cooling system at the expense of inefficient use of the cooling equipment. In the case of over-usage, the building's cooling capacity must be increased. Poor judgment in estimating IHG can result in unsatisfactory operation. As with building envelope loads, IHG estimating procedures are therefore rigorous and precise using the best information available for the given type of building.

Latent heat (moisture or water vapor) from people and equipment added to the space is an instantaneous cooling load. Sensible heat generated by internal heat sources (people, lights and equipment) is a time-delayed cooling load. As with solar radiation heat entering the space, part of sensible heat generated by internal sources is first absorbed by the surroundings and then gradually released into the air increasing its temperature. The air temperature is sensed by the control system (thermostat) which operates the cooling system and equipment. So there is a time-delay in the corrective action also.

To allow for the time delay due to thermal storage, Cooling Load Factors (CLF) was developed to estimate the heat gains from internal heat emitting sources. CLFs are based on the time (hour) when the internal source starts to generate heat load and the number of hours it remains in operation.

- **Shifting of heat sources within the installation**

In some buildings, the internal heat sources shift to the different area of the building during the different time periods of the day. For an example, in a hotel, the occupants leave their rooms and gather at the restaurant for lunch and dinner. In this instance, the heat gain at some zones of the building reduces while the heat gain at another zone is increasing by the same magnitude thus without significant change to the total internal heat gain of the building. Using the VRV air-conditioning system, the total equipment capacity could be optimized maintaining the energy efficiency of the system at desired level.

2.5 Previous studies on the VRV systems

VRV air-conditioners were introduced to the market in the recent past. Before introducing to the market in commercial level, lot of Research and Developments had been taken place to improve the technology to market it as a commercial appliance. Even after introducing VRV air-conditioners to the market, the technology has further been developed by the manufacturers to create the market competition and to minimize the technical problems encountered in the introductory phase of them. However, no trace of a record was found regarding a comprehensive research study carried out on the VRV systems in Sri Lanka or in a recognized foreign institute except some limited number of research studies on the energy performance of the VRV systems.

2.5.1 Experimental studies

A study had been conducted by Tolga N. Aynur on Variable refrigerant volume systems in July 2010 [12] and it presents a detailed overview of the configurations of the outdoor and indoor units of a multi-split variable refrigerant volume system, and its operations, applications, marketing and cost. Besides, a detailed review about the experimental and numerical studies associated with the VRV systems provided. The aim of the study had been to put together all the diversified information about the VRV systems in a single source. According to detailed review, it had been observed that the compressor frequency and the electronic expansion valve opening should be controlled simultaneously for the control strategies, and it had been concluded that VRV system not only consumes less energy than the common air conditioning systems such as variable air volume, fan-coil plus fresh air under the same conditions, but also provides better indoor thermal comfort as long as it is operated in the individual control mode. It was found that even though the main drawback of the VRV system is the high initial cost compared to the common air conditioning systems, due to the energy saving potential of the VRV system, the estimated payback period of the VRV system compared to an air cooled chiller system in a generic commercial building could be about 1.5 year.

Masuda et al. developed a control method for a multi-split VRF system with two indoor units. The new control method showed that, the refrigerant flow rate for the indoor unit installed to a room with higher cooling load was much more than the other indoor unit. It was obtained that the compressor frequency decreased when each room temperature reached to the setting temperature, and increased in the opposite case. It was concluded that the new control method could control the refrigerant flow rate of the indoor units individually and respond to the cooling loads. Xia et al. applied a testing methodology to a multi-split three-pipe VRV system having five indoor units. The tests were performed in six calorimeters; the outdoor and indoor units were placed in each calorimeter. The coefficient of performance (COP) of the system was defined as the ratio of the total thermal load to the total electric consumption of the system. All the tests were performed in ‘‘cooling all’’ mode and without any latent load. It was found that the COP of the system did not vary too much according to the part load ratio. This was explained by the use of two compressors in ‘‘tandem’’, which yielded good part load performance. The COP of the system was obtained within 1.9–2.4 for the ‘‘cooling all’’ mode.

Choi and Kim studied the performance of a multi-split VRV system having two indoor units with individual EEVs by varying the indoor loads, the EEV opening and the compressor speed. It was suggested that the superheats for both indoor units had to be maintained around 4 0C by adjusting the EEVs, and consequently, the compressor speed should be adjusted to provide enough cooling capacity for each indoor unit.

Hu and Yang [13] developed a cost effective, energy efficient, multi-split VRV system having five indoor units. A variable refrigerant volume scroll compressor was used instead of an inverter aided one. The capacity control of the compressor was performed by an ‘‘ON/OFF’’ switching of the solenoid valves which changed the position of a static scroll to provide variable refrigerant flow. The system determined the required load of the indoor units from the difference between the room and set temperatures, and regulated the degrees of each EEV opening to control the refrigerant flow and the evaporation temperature of each indoor unit. Meantime, the outdoor unit determined the running cycle and the output time of the refrigerant in the compressor according to the requirement of the indoor units to control the ‘‘ON/OFF’’ cycle time of the solenoid valves, which controlled the refrigerant volume of the compressor. It was found that the developed system could adjust the capacity within 17– 100% with a power input of 1.3–4.8 kW, on the other hand, the inverter system adjusted the capacity within 48–104% with a power input of 2.5–6.1 kW.

Hai et al. studied a multi-split three-pipe VRV system with a nominal capacity of 30 kW. The system was charged with R22 and consisted of five indoor units with different capacities. The experiments were performed under steady state conditions with different cooling and heating configurations, and it was found that the COP of the system increased in the ‘‘cooling-principal’’ and the ‘‘heating-principal’’ modes, because both condensing and evaporating capacities were used.

Designed and researched a multi-split VRF system having an ice storage tank. It was mentioned that with the ice storage tank, an additional 30 0C sub cooling could be achieved which increased the energy efficiency ratio (EER) about 25%. According to the economic evaluation based on the electric price of Shanghai, the payback period of the multi-split VRF system with the ice storage tank was found to be less than 3 years.

Aynur et al. [14] conducted a field-performance test with a multi-split VRV system in an actual office suite in order to provide real time operational characteristics of the system. Two different control modes (individual and master) were applied to the system. In the individual control mode, all indoor units were controlled by their own individual thermostats located into each zone. In the master control mode, all indoor units were controlled by only one thermostat which was located in the center of the office suite. First time in the open literature, a thermal comfort evaluation for a multi-split VRF system was performed with the ASHRAE thermal sensation scale (+3, +2, +1, 0, _1, _2 and _3 correspond to hot, warm, slightly warm, neutral, slightly cool, cool and cold, respectively). It was concluded that the multi-split VRF system in the individual control mode provided better thermal comfort for multiple rooms with higher efficiency compared to the master control mode.

Aynur et al. investigated the effect of ventilation on the indoor temperature control, thermal comfort, outdoor unit energy consumption and the efficiency of a multi-split VRV system integrated with a heat recovery ventilation system in a field performance test under varying outdoor conditions. It was observed that ventilation did not affect the indoor temperature control; instead it increased the indoor humidity ratio resulting in a less comfortable indoor environment according to the ASHRAE summer thermal comfort zone. It was also found that even though the ventilation increased the outdoor unit energy consumption due to the ventilation load (ventilation-assisted multi-split VRV system consumed 27.8% more energy than the non-ventilated one), it did not have a considerable effect on the efficiency of the multi-split VRV system.

Aynur et al. investigated the integration of a multi-split VRV system with a ventilation unit, a self-regenerating heat pump desiccant unit, in a field performance test. It was found that the heat pump desiccant unit provided better indoor thermal comfort than a heat recovery ventilation unit due to the better indoor humidity control. It was also concluded that since the heat pump desiccant unit took care of some portion of the cooling load, the outdoor unit of the multi-split VRV system consumed 26.3% less energy for the operation in conjunction with the heat pump desiccant unit as compared to the operation in conjunction with the heat recovery ventilation unit. Three different operating modes; non-ventilated, heat pump desiccant ventilation assisted and heat pump desiccant ventilation-dehumidification assisted VRV systems were investigated in the study of Aynur et al. It was found that the VRF systems provided an average of 97.6% of the total cooling energy of the heat pump desiccant ventilation assisted mode. The remainder was the recovered cool by the heat pump desiccant units during the ventilation. On the other hand, the VRV systems provided an average of 78.9% of the total cooling energy of the heat pump desiccant ventilation dehumidification assisted mode. The remainder was covered by the heat pump desiccant units which provided additional sensible and latent cooling.

Aynur et al. investigated the effects of the ventilation and the control mode on the performance of a multi-split VRV system integrated with a heat recovery ventilation system for the heating mode in an office suite. It was found that the heat recovery ventilation system decreased the indoor humidity ratio by introducing the low outdoor air humidity ratio to the indoors, resulting in a dry indoor environment. It was also found that due to the additional ventilation load; the ventilation-assisted multi-split VRV system consumed 35.2% more energy than the non-ventilated one.

2.5.2 Modeling studies

Park et al. [15] studied the system performance of a multi-split VRV system having two indoor units based on the compressor frequency, total cooling load, and the cooling load fraction between two zones (defined as the ratio of the cooling load of the first zone to the total cooling load). It was found that the compressor powers increased with a second-order of the compressor frequency with a reduction in the COP. By fixing the total cooling load of the system at 6 kW, it was obtained that the power consumption increased with an increase of the load difference between each zone with a reduction in the COP. The reason of the increase in the power consumption was due to the increase in the compressor operating frequency. It was observed that when the load ratio was changed from 50 to 100%, the compressor frequency changed only 30%, but the EEV opening changed about 92%. It was concluded that the major control parameter was the EEV opening in a multi-split VRV system rather than the compressor operating frequency when the load ratio was changed.

Xia et al. studied the performance of a multi-split three-pipe VRV system. Instead of ‘‘ON/OFF’’ operation of each indoor unit, a continuous adaptation of the heat transfer coefficient method was applied to maintain the same superheating in ‘‘ON’’ periods. In this control strategy, each EEV was adjusted individually to distribute the suitable refrigerant mass flow rate to each indoor unit in order to maintain the constant indoor room temperature.

Shi et al. developed a fluid network model to simulate the performance of a multi-split three-pipe VRV system having two indoor units. It was found that the EER of the system in heater recovery mode was about two times higher than the EER in ‘‘cooling-only’’ or ‘‘heating-only’’ modes, due to the usage of both cooling and heating capacities.

Xia et al. studied the operating characteristics of a multiple VRV system having three indoor units. It was found that the greater the EEV opening, the greater the mass flow rate through the indoor unit. It was obtained that for the same compressor speed, when the EEV opening of one indoor unit increased while the other two kept unchanged, the cooling capacity of the first indoor unit increased, while the cooling capacities of the rest decreased because of the distribution of the refrigerant mass flow rate. It was concluded that by adjusting the compressor rotation speed while keeping the suction pressure unchanged, the cooling capacity of the individual evaporators could be changed without affecting others.

Shah et al. developed a new methodology for the dynamic modeling of a multi-split VRV system. The expansion valve was modeled as an isenthalpic orifice, and the compressor was defined as a function of the compressor speed, volume of the compressor and the pressure ratio. It was found that the compressor could be used as a control actuator for a multi-split VRV system because of its direct influence on refrigerant flow rate. The EEV of the first evaporator changed, while the second one was kept constant, and it was found that the pressure in the second evaporator also changed due to the coupled system dynamics. It was concluded that a control algorithm should also include the EEV in order to maintain the pressure of the second evaporator at the desired value.

Wu et al. proposed a control strategy for a multi-split VRV system having three indoor units. The suction pressure and the room air temperature were taken as the control parameters to modulate the compressor speed and the EEV opening, respectively. A self-tuning fuzzy control algorithm with a modifying factor was also input in the controller. The parametric tests showed that the proposed control strategy with the fuzzy control algorithm could achieve the desired control accuracy of the controlled parameters.

Zhou et al. [16] investigated the performance of a multi-split VRV system with the Energy Plus dynamic building energy simulation program. A module for the multi-split VRV system was developed and imported into Energy Plus. The module could give the power and energy consumptions of the indoor and outdoor units, as well as the COP and the part load ratio. It was found that the COP of the multi-split VRV system increased when the system worked in part load conditions due to the high part load efficiency. Besides, the developed model was used for a comparison study performed in a 10-story office building in Shanghai. It was obtained that the multi-split VRV system saved more than 20% energy compared to a variable air volume system and more than 10% compared to a fan-coil plus fresh air system. Lin and Yeh studied a three-evaporator air conditioner for a feedback controller design. For the proposed control structure, the three evaporating temperatures were controlled by the EEV openings in order to keep the indoor temperatures at the set points with no steady-state errors. Besides, the compressor speed was used to control the three superheat temperatures associated with the three evaporators. The proposed control method was experimentally validated.

Further, In order to make a comparison between VRF and traditional window air-conditioners a simulation run with one window air-conditioner per-zone scheme was established for a three zone single storey building model. That means each zone was served by one window air-conditioner. With all the indoor units or window air-conditioners working in the simulation, Figure - 1 shows the daily absolute changes of the COP value for the VRF system and corresponding alternative window air-conditioners in the three zones. It can be shown that COPs in both systems achieve their highest point one after the other between 8:00 and 10:00, and their lowest points during 13:00–15:00. The diurnal variation between maximum and minimum COP gets up to 1.12 for the VRF system, compared to 0.5 for window air-conditioners. In other words, it denotes that the VRF system has a more flexible and sensitive response to the cooling loads in the whole-day running, compared with the window air-conditioners. It reflects the ability of VRF on tracking cooling load duly at a higher operational efficiency. Meanwhile, the COP value of the VRF system keeps much higher than those of the window air-conditioners. This result indicates the superior performance at part load for the VRF system.

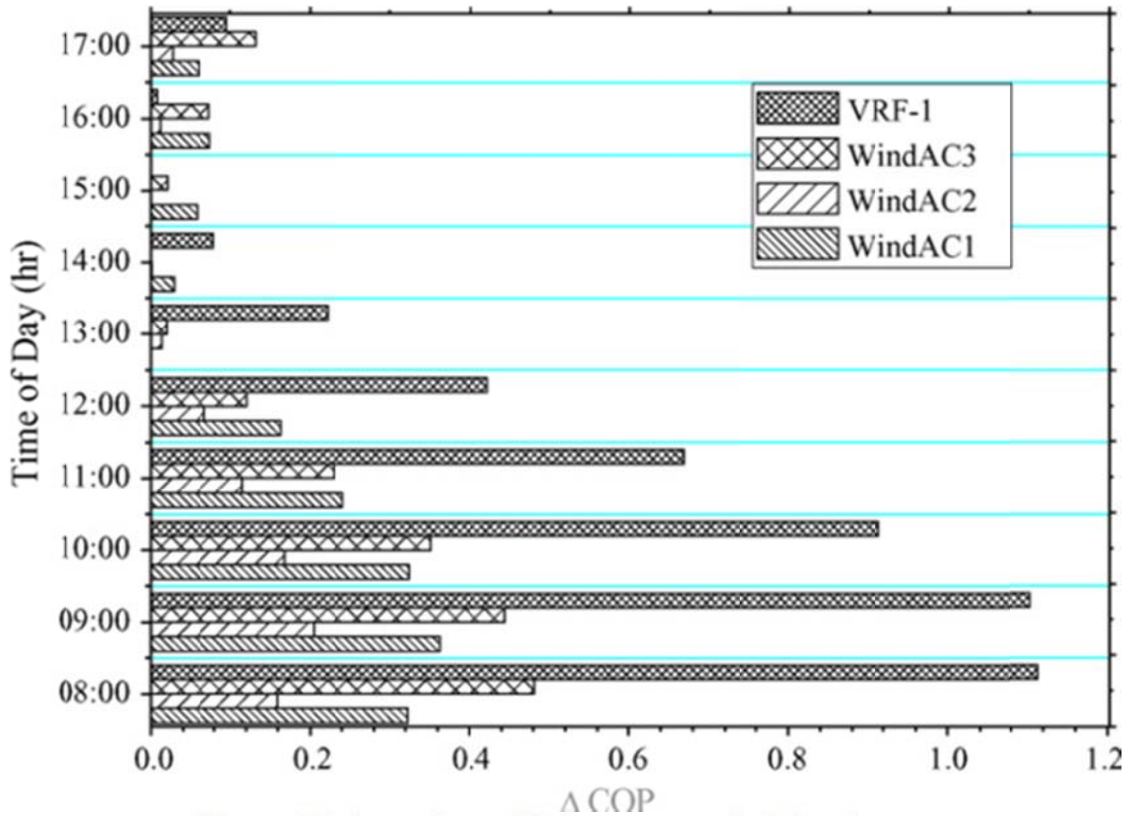

Figure 1 : Comparison on the daily amplitude between VRF-1 system and the window air-conditioners.

Aynur [17] investigated the performance of two VRF systems integrated with heat recovery ventilation units numerically with DOE's building simulation package in an existing office suite which had a total area of 167.3 m2 during the cooling season of 2007. Simulations were performed under four different U.S. climate conditions. The locations were selected to cover the entire range of weather conditions ranging from cold to hot temperatures and dry to humid weather: cold and moderate humid climate (Los Angeles, CA), mild climate (College Park, MD), hot and humid climate (Houston, TX), and hot and dry climate (Phoenix, AZ). For the period of June–August 2007, Los Angeles was found to be the coldest location with the monthly average outdoor temperatures of 17.7 0C (June), 20.5 0C (July) and 21.2 0C (August), and Phoenix was found to be the hottest location with the monthly average outdoor temperatures of 34.2 0C (June), 35.4 0C (July) and 35.5 0C (August). On the other hand, Houston was the most humid location with the monthly average outdoor humidity ratios of 0.0171 kg/kg (June), 0.0176 kg/kg (July) and 0.0182 kg/kg (August), and Phoenix was the driest location with the monthly average outdoor humidity ratios of 0.0041 kg/kg (June), 0.0103 kg/kg (July) and 0.0116 kg/kg (August).

Overall, a wide range of outdoor temperature (from 10.6 to 45.6 0C) and a wide range of humidity ratio (from 0.0015 to 0.0216 kg/kg) were covered with the selected locations. The VRV systems integrated with the heat recovery ventilation units were operated 24 h a day, 7 days a week during the period of June-August 2007. In CA for an indoor set temperature of 27 0C, the seasonal total energy consumption of the whole system was found to be 3200.5 kWh, and it increased by 12.9% and 27%, when the set temperature decreased from 27 to 25 0C and 23 0C, respectively. On the other hand, for the set temperature of 25 0C, the seasonal total energy consumptions in MD, TX and AZ were found to be 46%, 2.08 times and 2.45 times higher than in CA.

Aynur et al. investigated the effect of ventilation on the indoor temperature control, thermal comfort, outdoor unit energy consumption, the efficiency of a multi-split VRV system and energy saving options. The multi-split VRV module obtained from Zhou et al. was used. A control strategy for the multi-split VRV system integrated with the heat recovery ventilation units ‘‘synchronized indoor fan operation with economizer’’, was proposed, which promised 17–28% energy savings when compared with the ‘‘continuous indoor fan operation without economizer.’’

Aynur et al. compared the performance of two widely used air conditioning systems, variable air volume and multi-split VRF, in an existing office building environment under the same indoor and outdoor conditions for an entire cooling season. It was found that the secondary components (indoor and ventilation units) of the multi-split VRV system promised 38.0–83.4% energy-saving potential depending on the system configuration, indoor and outdoor conditions, when compared to the secondary components(heaters and the supply fan) of the variable air volume system. Overall, it was found that the multi-split VRF system promised 27.1–57.9% energy-saving potentials depending on the system configuration, indoor and outdoor conditions, when compared to the variable air volume system.

Li et al. developed an energy plus module for a water cooled multi-split VRV system. After modeling and testing the new model, on the basis of a typical office building in Shanghai, the monthly and seasonal cooling energy consumption and the breakdown of the total power consumption were analyzed. The simulation results showed that, during the whole cooling period under the humid subtropical climate condition, the fan-coil plus fresh air system consumed about 20% more power than the water cooled VRF system.

Liu and Hong presented a preliminary simulation comparison of the energy efficiency between an air-source heat recovery multi-split VRV system and a ground source heat pump system. A small office building with a conditioned floor area of 360 m2 was selected, and the building required simultaneous heating and cooling year round. Two cities were selected to represent the hot and cold climates of the US; Miami and Chicago. It was found that the ground source heat pump system saved 9.4% and 24.1% electricity compared to the multi-split VRV system for the same office building located in Miami and Chicago, respectively. It was concluded that electricity savings goes up with the increasing heating demands.

The VRV technology refers to the ability of a system to control the refrigerant mass flow rate according to the cooling and/or heating load, enabling the use of as many as 60 or more indoor units of differing capacities and configurations with one single outdoor unit, individualized comfort control, simultaneous heating and cooling in different zones, and heat recovery from one zone to another. The above studies indicate that the researchers focus on three main subjects: Control strategies of the variable speed compressors and the electronic expansion valves (EEVs), field performance testing and integration with the ventilation systems and comparisons of the energy consumption and thermal comfort with other common air conditioning systems.

It is observed that the compressor frequency and the EEV opening should be controlled simultaneously for the control strategies. Considerable focus should be oriented towards the integration with the ventilation systems, because poor integration causes not only worse indoor thermal comfort, but also more energy consumption due to the additional ventilation load. For the system performance comparisons, for the cooling season, based on the available studies, it can be concluded that the multi-split VRV system not only consumes less energy than the common air conditioning systems such as variable air volume (from 20 to 57.9% under the humid subtropical climate), fan-coil plus fresh air (10% under the humid subtropical climate condition), chiller/boiler system (35% under the humid subtropical climate condition), chiller system (30% under the tropical climate condition), but also provides better indoor thermal comfort as long as it is operated in the individual control mode. On the other hand, for the heating season, based on the available study, it can be said that the ground source heat pump system consumes 24.1% less energy than a heat recovery multi-split VRV system under the cold climate condition.

The detailed review reveals that even though the main drawback of the multi-split VRV system is the high initial cost compared to the common air conditioning systems, due to the energy saving potential of the multi-split VRV system, the estimated payback period of the multi-split VRV system compared to an air cooled chiller system in a generic commercial building could be about 1.5 year. However, there is still a necessity to develop cheap multi-split VRV technology in order to increase the market potential and the energy saving advantage.

2.5.3 Case studies

As an application of the VRV energy-calculation module in Energy Plus, a comparative energy studies is conducted among three popular HVAC systems in China, namely, VAV, FPFA, and VRV. In this study, various systems are examined so that their applicability and features can be identified from the energy use's point view by simulation analysis.

2.5.3.1 Scope of the study

A general 10-storey office building is developed to serve as a platform which can accommodate different air-conditioning systems for the purpose of comparison research. How to select the building type and materials for evaluation of different kinds of HVAC systems is based on the commercial building studied by Li et al. [18]. However, in this study, some of the building envelope features are modified to meet the present research conditions. Each floor of the building is divided into six conditioned thermal zones, corresponding to four outside exposures (north, east, south, and west), the interior zones, and the center core.

Table 1 : Brief descriptions of the sample building and HVAC systems

Items	Description
General information • Location • Building type and stories • Air-conditioned area • Floor area and height • Windows and shading	• Shanghai, China • Office building, 10 stories above ground • 7840 m^2 • 28 m Â 28 m; floor- to- floor height = 3.5 m • Low-e double pane glazing. Window height = 1.5 m; sill height = 0.80 m; • WWR = 30%. No shading device • ON during weekdays: 7:00–17:00; OFF during all other days
Operation hours **Design values of internal heat gains,** • Ventilation, and infiltration • Occupancy density • Lighting density • Plug equipments load • Space design temperature • Infiltration • Ventilation • Night setup • Running period	• 5 m^2/person (perimeter and interior zones), 25 m^2/person (center core) • 25 W/m^2 (perimeter and interior zones), 15 W/m^2 (center core) • 20 W/m^2 (perimeter and interior zones), 0 W/m^2 (center core) • 25.0 ^{0}C • 0.1, air change per hour for each zone • 4.0 $m^3/(m^2\ h)$ (perimeter and interior zones), 0.6 $m^3/(m^2\ h)$ (center core) • 37 ^{0}C • June 1–August 31, typical summer days in Shanghai (Ref. Weather file CTYW.STAT)
HVAC system and plant information • HVAC systems (with same cooling capacities) • Chiller types • Cooling source nominal COP (kW/kW) • Fans and pumps	• VAV no-reheat; fan-coil plus fresh air (FPFA) VRV • Water-cooled screw chiller • Screw chillers for VAV and FPFA: 4.6; VRV units: 3.02 • Variable speed drive (VSD) for the central fan and chilled water loop pumps in the VAV • system; VSD for chilled water supply pumps in the FPFA system

The typical floor in the simulation incorporates a floor multiplier of 8 to account for the actual number of middle floors in the building. A summary of the key parameters of the building is given in Table 1, construction material properties is listed in Table 2, and the typical floor plan is shown in Figure 2. In this investigation, the following assumptions are made.

- All the floor plans in the sample building are the same. There are not basement spaces underneath the building.
- Only one type of HVAC system is installed to serve the building in each case.
- The indoor air set points are identical everywhere in the building.
- A single chiller serves the whole building, while a VRV system per floor supplies needed cooling.

Table 2: Construction thermal properties

Layers (outer to inner)	**Thickness (mm)**	**Conductivity (W/(m**	**Density**	**Specific heat (J/(kg**
Exterior wall • Cast concrete • XPS extruded polystyrene • Air gap	1501.13 200.034 Thermal resistance $R = 0.18\ m^2\ K/m^2$ 150.2		2000 35 2800	1000 1400 896
Interior wall • Plaster (lightweight) • Cast concrete • Plaster (lightweight)	13 100 13	0.16 1.13 0.16	600 2000 600	1000 1000 1000
• Ceiling/floor (the order of floor materials is the reverse of that of ceiling materials) • Cast concrete1501.13 • Air gap thermal resistance $R = 0.18\ m^2\ K/m^2$ • Plasterboard100.16			2000 950 2700	1000 840 753

The water-cooled type chiller and the VRV equipment from the same manufacturer are chosen to meet the cooling demand. There are neither shading devices associated with the building envelope, nor any adjacent tall buildings that would bring on daytime shading. There is no roof glazing or skylights in the sample building. The geographical and weather file, infiltration, thermostat, and other parameters related to building load calculations are the same for all the HVAC systems simulated

2.5.3.2 Results and discussion

A series of simulation are implemented for the performance comparison of the HVAC systems in this section. The results of the simulations for evaluating systems are presented in categories that describe the energy consumption shares of the electricity end-users in systems such as VAV, FPFA, and VRV. Results show the differences among systems, as reported in Fig. 11. The breakdown of the total electrical energy consumption into various parts include system fans, chillers, pumps, space lighting, plug equipment, and VRF system. Energy usage of drink-water pumping, lifts, and other non-HVAC related power facilities is disregarded in electricity-usage breakdown of end-users in the study. In this figure, ‘‘system fans’’ means the central supply fan in VAV, or the aggregate of individual fans in FPFA, or the aggregate of indoor unit fans in VRV; ‘‘chillers’’ denotes energy consumption of chillers; ‘‘pumps’’ refers to the chilled water and cooling water pumps; ‘‘VRV systems’’ stands for the energy input of VRV outdoor units containing condenser fans, compressors, and control circuits; while ‘‘heat rejection’’ is the tower fan electric consumption.

2.5.3.3 Breakdown of electricity end-users in HVAC systems

For the VAV system, lighting and plug load share a part of 46%, chillers 33%, system main supply fan 11%, water pumps 7%, and heat rejection keeps the left 3%; for the FPFA system, lighting and plug load share a part of 52% together, chillers 32%, indoor fans, system water pumps, and heat rejection hold 6%, 7% and 3%, respectively; for the VRV system, lighting and plug load own a part of 58%, the VRV system and indoor fans take the residual part 42%.

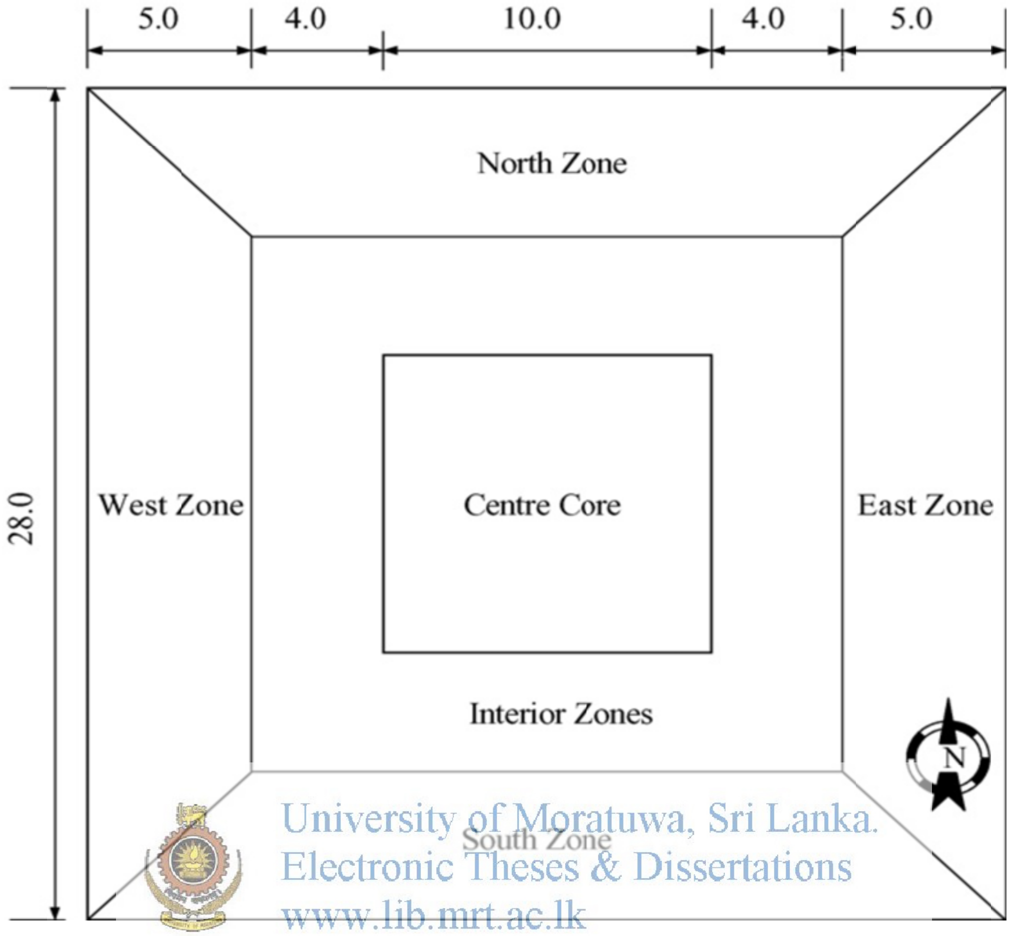

Figure 2 : Typical floor plan of the sample building (unit in drawing: meters)

As the second largest energy consumer in the VAV system, the main air supply fan takes a remarkable larger part of electricity use than the indoor fans used in the FPFA and VRV systems. This share by the VAV supply fan is still much less than the survey data for a typical office building, whereas it agrees well with the simulation result of 14.1–28.3% of the HVAC system consumption [19] comparatively. It can be explained that unreasonable choices and operation strategies of air transport facilities exist commonly in reality. On-site measured data do not mean rational data. In a sense, thus, energy simulation of HVAC systems is able to put forward a gap as reference between the ideal consumption and the actual consumption of equipment.

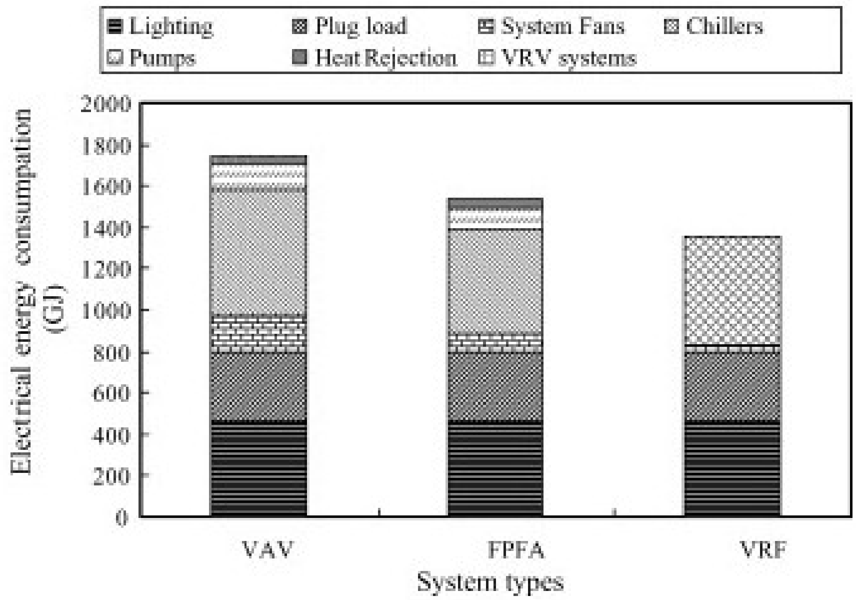

Figure 3 : Comparison of energy usage among three systems

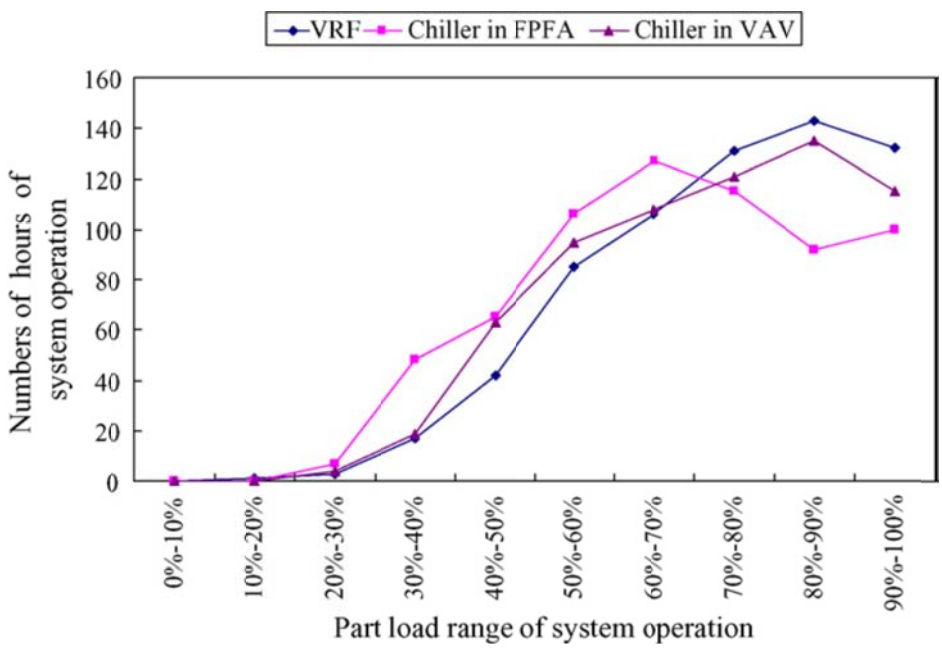

Figure 4 : Part-load range of the three kinds of systems.

The indoor fan in the FPFA system uses 6% of energy, and its absolute magnitude locates in the middle of the fan energy in other two systems. It can be understood that there is a strong relationship between the fan energy and the type of cooling media. Specific enthalpy of refrigerant in the VRV system is much greater than water and air in the other systems, and phase change takes place in the indoor evaporator, which are both believed to bring out less fan energy.

For the VRV system, the indoor fans' contribution to the whole VRV system's energy usage is 7%, according with the experimental result 9.8% on the whole, considering diversity of application conditions and equipment series.

2.5.3.4 Electricity consumption of different systems

HVAC systems can be categorized to the all-air system, the water–air system, and the refrigerant system in accordance with the kinds of cooling media. Fig. 11 depicts the electricity usage for HVAC systems. The VRV system is the most energy efficient one among three sample cooling systems, followed by FPFA, while VAV ranks last, as shown in the figure. It denotes that an all-air system like VAV consumes more energy than either a water–air system (FPFA in this case) or a refrigerant system (VRV in this case), even though it is usually regarded as a high-efficiency system. The superiority of a VAV system is significant only if it is compared with a conventional constant air volume system.

The VRV system uses 11.7% less electrical energy than the FPFA system with a variable speed drive (VSD) loop water pump, 22.2% less electrical energy than the VAV system outfitted with a VSD fan in this case. Owing to air-conditioning systems working usually off the rated condition, the part-load performance of the refrigeration equipments plays a significant role in final electricity usage of the building. The number of working hours of the three systems based on different part-load ranges in this study is presented in Fig. 12. The profiles of part load show some differences, which are believed to be induced by diverse humidity levels during the simulation. Keeping the indoor air temperature at set point, the thermostat control makes the space humidity drift and results in various latent load and then the various total load. It can be seen from this figure that a notable majority of operation hours of all the VRF, FPFA, and VAV systems occurs between 30% and 90% part-load operating conditions. The accumulative totals account for 79.3%, 83.7%, and 81.9% in the overall 660 operation hours for the VRV units, the chiller in the FPFA system and the chiller in the VAV system, respectively. It offers the VRV system an occasion to perform within its favorable energy-feature range in a significant part of working time. In other words, the VRV system is provided with a high efficiency at partial load condition and works at the condition in an essential part of operation time, which may be considered as one of reasons for its less energy usage. It may be established the more the VRF system works in the favorable part-load range, the more energy savings can be achieved. As the cooling resources and the substantial energy consumers in other two HVAC systems, the screw chillers take similar efficiency at part load with that at full load [20]. Compared with the VRV system, this feature makes the chiller less sensitive to changes of the cooling load. Meanwhile, the refrigerant from nearby outdoor units in the VRV system goes directly to conditioned zones to exchange heat with air. By contrast, the chiller needs one or two secondary heat-transfer process to pipe the low-specific enthalpy cooling media, water or air, through a long way to cool the zones in the building. It tends to result in large heat exchange and transport loss and inevitably gives birth to added energy consumption.

2.5.3.5 Conclusion of the case study

Computer simulation is a convenient tool of assessing building energy performance, air-conditioning system features, and system operational strategies. It allows users to test their ideas and designs to see what the impact of their decisions would be on energy consumption and other aspects. In this study, a new module is developed in the BESP program Energy Plus, in order to evaluate the benefits of the VRV system under cooling condition in terms of energy usage. A case study is then made to demonstrate the application of the new module for the VRV air-conditioning system in a medium-sized office building.

Simulation results from the electricity-usage comparison among VAV, FPFA, and VRV systems implies that the VRV air conditioning system is the most energy efficient, compared with other two conventional systems. The energy-saving potentials of the VRV system are expected to achieve 22.2% and 11.7%, compared with the VAV system and the FPFA system, respectively. With the same nominal cooling capacity, the VRV system and VAV (or FPFA) plus chillers system consume notably different electricity energy, due to various ways in transporting cooling media and diversity of part-load performance. This study provides architects and engineers some ideas to analyze the energy features of the VRV system and to evaluate different systems by the view of energy characteristics, especially during the primary conceptual design stage.

It is pertinent to note that influencing factors of the energy consumption of air-conditioning system is fairly complicated in real buildings. Building designs, constructions, operation strategies, chillers configuration, maintenances, and other unpredictable ingredients can impact on the eventual facility bills for buildings. Simulations offer an ideal benchmark of energy usage of the integration of the building, air-conditioning systems and artificial interference under a certain condition, rather than a predetermined augur. But this investigation still owns its sense in suggesting the VRV system may be an attractive option and a more efficient operation for a new installation or a changeover from an inefficient old system, by an energy use perspective.

The future work will include the economic evaluation and life-cycle cost analysis of various forms of HVAC systems. Also, electricity-usage field tests of the VRV system are underway, as a part of the extension of this research, so that the results can be verified. Further, the VRV system's performance in heating condition would be researched.

2.5.4 Overall summary of the literature review

The use of VRV air conditioners has been considerably widened during the recent past. The technology becoming popular day by day due to its high performance and advance features. The above literature review focused on some experimental, modeling and case studies.

The experimental studies shows that VRV system perform efficiently than the common air conditioning systems such as variable air volume, fan-coil plus fresh air under the same conditions whilst providing better indoor thermal comfort in the individual control mode. It had been noted that the VRV system performs at its best efficiency when operated in cooling and heating modes simultaneously due to the use of condensing and evaporating capacities. Though the main drawback of the VRV system is the high initial cost compared to the common air conditioning systems, the estimated payback period of the VRV system compared to an air cooled chiller system in a generic commercial building could be in the order of one to two years under the conditions that had been assumed for studies. Modeling studies shows that the COP of the multi-split VRV system increased when the system worked in part load conditions due to the high part load efficiency. They further shows that the saving potential of VRV systems compared to chiller systems could be in the range of 10 % to 20 % for medium scale commercial buildings under the assumed conditions. Case study shows that even though VRV systems have better energy performances, the main drawback is their high initial cost compared to the other common air conditioning systems.

From all the studies it has been generally deduced that, there is still a necessity to develop cheap VRV technology in order to increase the market potential and the energy saving advantage.

CHAPTER 03

Methodology

3 Methodology

For the development of any trade, experience of involved stakeholders is very valuable. Even for this study, experience of stakeholders is equally important. In case of VRV air-conditioner installations, experience of designers, consultants, contractors, owners, maintenance engineers and managers are rather important as they have involved with the entire processes from the preliminary study to the operation and maintenance of the system. Their inputs, opinions, views and recommendations are very important to make the outcome of any research study realistic. Therefore, it was decided to explore experience, opinions, comments and recommendations of the personnel involved with the above installation on the maintainability, energy efficiency and suitability of VRV air conditioners wherever possible to supplement and strengthen the study.

3.1 Appropriate method selected for the collection of information

In general, the most appropriate method of analyzing the experience and opinions of stakeholders is an opinion survey. The sample size of opinion survey is generally determined base on the population and expected accuracy. For general information survey, the accuracy will be higher when the sample size is more. But, in this type of technical information and experience survey, Conventional market research methods do not work well [21]. Sample size is not a vital parameter in the case of survey on experience on many new industrial technologies. Cornelius Herstatt and Eric von Hippel report on a “lead user” method for developing concepts for new technologies / products revealed that the richest understanding of emerging new technologies is held by just a few users. It is possible to identify these “lead users” and then obtain the required information from them based on their experience [21]. According to the report published by Louis M. Rea and Richard A. Parker, the concept of considering the information delivered by a smaller number of representative people to be an accurate representation of a significantly larger number of involved persons has become a familiar and practical method of collecting information on a technology with a limited use [22]. Therefore, it was decided to perform a case study on a representative VRV installation to study the objectives instead of conducting an opinion survey of a large number of stakeholders.

3.2 Installation selected for the study

As described above a representative installation was selected for the comprehensive study to determine the, followings.

- Understand whether the prevailing demand for VRV air-conditioners is really because of its ability to cater the desires of purchases and users.
- Estimate the saving potential of VRV air-conditioners compared with the other available potentially applicable air-conditioning systems for the purpose and financial analysis.
- Study the maintainability of VRV air-conditioning installations based on the information collected from the Owner / Maintenance Manager of an identified representative building where a VRV air conditioning system has been installed.

To achieve the above objectives, following factors were thoroughly analyzed with respect to the installation selected for the study.

- Factors considered by the designers, project team and owners in selecting the VRV air-conditioning system for the building.
- Maintainability of the system and problems encountered by the owners of the building with regard to the maintenance of the air-conditioning system.
- Energy efficiency of the VRV air-conditioning system and its saving potential and whether the expected benefits have been gained by the building owners.
- Whether the suppliers/contractors has maintained the system to the satisfaction of building owners
- Whether the VRV technology is suitable for the building

The representative installation selected for the comprehensive study is the Sovereign Residencies. The sovereign corporate hotel belongs to Center for Banking Studies, situated at No 100C, Sri Jayawardanapura Mawatha, Rajagiriya. The hotel building consists of 64 numbers of rooms that almost equally built in 3 numbers of apartments. Main restaurant and a kitchen are located in ground floor. In addition to those three apartments the basement is used for different purpose such as tool rooms, stores, rest rooms, infrastructure facility to staff etc.

The main functions of this hotel are to provide accommodations to local and foreign guests, provide facilities for different functions and trainings etc. Food is served to the rooms on request basis and the main restaurant is used especially for arranged functions. This installation was selected for the study as the VRV air-conditioning system installed in this building is nearly five years old and access to the information is not restricted.

3.3 Methodology followed for the study

After selecting the Sovereign Residencies, as the representative installation for the study, following methodology was adapted to achieve the research objectives.

- The building and the air conditioning system were inspected.
- Design drawings and design correspondence were referred.
- Project correspondences (including the correspondence related to the procurement process) which are in the official project files were referred.
- Maintenance correspondences in the maintenance files were referred.
- Discussions were held with the officers who got involved with the project in the preliminary stage, procurement stage, installation stage and maintenance stage.
- Information was obtained from the above discussions and documents. The useful and relevant information from the gathered information were analyzed to achieve the research objectives.
- Computer simulation was performed using EQUEST simulation tool to compare the energy consumption pattern of different air-conditioning options that had been considered by the project team during the preliminary stage.
- Actual energy consumption records were used to calibrate the outcome of the simulation.
- Life cycle costing for the considered options were performed to analyze the financial viability of them.
- Sensitivity analysis was done for 10 % variation of initial investment and electricity tariff.
- Conclusion and recommendations were developed based on the observations of above studies and analysis.

CHAPTER 04

Comprehensive Study on a VRV Installation and Analysis

4 Comprehensive Study on a VRV Installation and Analysis

As described in the previous chapter, a comprehensive study on a representative VRV installation was performed to cover the following key areas,

- Understand whether the prevailing demand for VRV air-conditioners is really because of its ability to cater the desires of purchases and users and whether the owner and technical team has selected the appropriate air-conditioning system for the installation
- Estimate the saving potential of VRV air-conditioners compared with the other available potentially applicable air-conditioning systems for the purpose and financial analysis.
- Study the maintainability of VRV air-conditioning installations based on the information collected from the Owner / Maintenance Manager of an identified representative building where a VRV air conditioning system has been installed.

The installation selected for the above study is the Center for Banking Studies of the Central Bank of Sri Lanka.

4.1 Installation selected for the study - Center for Banking Studies

4.1.1 Description of the installed air-conditioning system

Center for Banking Studies is the training center of the Central Bank of Sri Lanka. It is located in Rajagiriya and consists of two major building blocks. The main building block is a three storied building where administrative offices, lecture rooms, and auditorium are located. This building has a central air-conditioning system for the auditorium. Administrative offices and lecture rooms have been air-conditioned by split type air-conditioners. The other major building block is the hostel block of the Center for Banking Studies which provide accommodation for the participants of the residential training programs conducted by the Center for Banking Studies. Lots of national and international training programs and workshops are conducted by the Central Bank of Sri Lanka through the Center for Banking Studies and this hostel block provides accommodation for the participants. Layout drawings of the building are attached in Annexure B

The hostel block of the Center for Banking Studies is a basement plus three storied building which comprises of 64 numbers of bed rooms that almost equally built in three numbers of apartments. Main restaurant and a kitchen of the hostel block are located at the ground floor. In addition to those three apartments, the basement is used for different purposes such as tool rooms, stores, rest rooms, infrastructure etc. About seven years back, this building was totally renovated and all the building services were reinstalled. Accordingly a new air-conditioning system was also installed at the building and it is a VRV air conditioning system. After the renovation project the management of the hostel building was outsourced and it is presently being managed by BMICH as a hotel.

Accommodation facilities for the local and foreign programs conducted by the CBS is also provided by the hostel block (hotel).

4.1.2 Description of the installed air-conditioning system

The air conditioning system installed in the building is an air cooled VRV air conditioning system. It comprises of six independent VRV air conditioner sets. These six sets of VRV air-conditioners have been used to condition the 64 bedrooms in the three floors of the hostel building. There are two VRV air-conditioner sets to cater each floor and the two sets are dedicated for the left and right wings of that particular floor. The ground floor consists of two numbers of outdoor units each having the capacity of 8 RT. Each of these units caters for 10 numbers of indoor units in the respective wing. The first floor also consists of two numbers of outdoor units of the same capacity and connected in the similar arrangement with the 11 numbers of indoor units in each wing. Capacity of the two outdoor units connected to the second floor is 11RT each and connected to 11 indoor units in the respective wing. All the indoor units are of the same capacity and the capacity of one indoor unit is 0.8 RT. All the outdoor units have been installed at the back yard of the hostel block in a row parallel to the rear wall of the hostel block building. The insulated copper refrigerant pipes have been laid through the ceiling space and drain of each indoor unit has been connected to the bathroom of respective room. Details of the equipment connected to the system are as follows.

- Brand – Mitsubishi
- Type – Air Cooled VRV air-conditioners
- Capacity
  - ✓ Indoor units - 0.8 RT (64 nos. installed in 64 bed rooms)
  - ✓ Outdoor units - 8 RT 4 nos.+ 11 RT - 2 nos
    - Installed at the ground floor back yard of the building

4.2 Selection of appropriate air-conditioning system for the building

The management of the Central Bank of Sri Lanka had considered three options for the type of air-conditioning system to be installed at the hostel. The brief descriptions of those three options are as follows.

- Installation of split type air-conditioner for each bedroom
- Installation of a chiller to cater the entire air-conditioning requirement of the building and to provide fan coil units for the bedrooms and individual rooms used for other purposes. Air conditioning for the main restaurant and entrance lobby was planned through an AHU connected to the same chiller.
- Installation of a VRV air-conditioning system for bedrooms and installation of split air-conditioners for other rooms. Air conditioning for the main restaurant and entrance lobby was planned through an independent package air-conditioning system.

This renovation project had been carried out under the Premises Department of the Central Bank of Sri Lanka and the license officer cum engineer in charge of the project was Mr. K L L Fernando. Information was obtained from him regarding the facts that he and the project team had considered on behalf of the Central Bank of Sri Lanka when selecting the appropriate type of air-conditioning system for the hostel block building. The facts explained by him are summaries as follows.

4.2.1 Installation of split type air-conditioners

The easiest option they had for the air-conditioning of the hostel block was split type air conditioners. But, the major problem they had with the split type air-conditioners was the appearance. For split type air conditioners, it is required to install 64 numbers of outdoor units only for bedrooms. The number of outdoor units required for the entire building was around 90. Technical team involved with the designing of the air-conditioning system pointed out the advantages and disadvantages of the installation of split type air-conditioners as follows.

Advantages: As each bed room has an individual air-conditioner, the respective unit can be operated when a room is occupied only. Also, the individual occupant can control the indoor temperature according to their preference. In case of the failure of one air-conditioner, only the respective bedroom will be affected.

Disadvantages: Split air-conditioning system is not the most appropriate type of air-conditioner system for this building in terms of energy efficiency. Installation of 90 odd outdoor units in the building will adversely effect on the appearance of the building. Outdoor units, when installed in large numbers in the balconies and corridors, it may disturb the calm surrounding environment.

The appearance and calm environment were among major concerns of the Central Bank of Sri Lanka as they had an intension of developing the hostel block to a star class hotel standard to attract international banking institutes for training programs. Therefore, the option of installing split type air conditioners wasn't accepted by the project team. They also considered about the comparatively low energy efficiency of split type air conditioners in arriving at this decision.

4.2.2 Installation of a chiller

The project team considered installation of a chiller as an appropriate option as the hostel block is a medium scale building. The advantages and disadvantages that the project team had identified are as follows.

Advantages: There wasn't a concern with regard to the appearance of the building as there were no many types of equipment to be installed outside the building. The only item to be installed outside the building was the cooling tower which was possibly be installed in the backyard of the building without disturbing the appearance of the building. Energy efficiency of an average chiller system was around 0.5 - 0.7 kW/RT and it was significantly higher than the typical energy efficiency of 1 - 1.2 kW/ RT of a good quality split type air conditioner.

Disadvantages: As the chiller installation was a central system, a standby chiller was also required to maintain the reliability of the air-conditioning system. Even with a chiller having multiple compressors, it is required to maintain at least a 50 % standby capacity to assure the reliability. Further, a substantial space was required to be allocated to the chiller plant room from the limited space available at the basement. When, the area was allocated for the plant room, there was a space problem for the other operational services of the hotel. The basement has a lower head room around 2 m. If chilled water and condenser water pipes were installed in the basement access for certain areas would have been disturbed. The team also observed that the clear ceiling space available inside the building (between the soffit and ceiling) to lay chilled water pipes was very small.

4.2.3 Installation of a VRV air-conditioning system

The third option of air-conditioning system considered by the project team for the hostel building was an air-conditioning system with VRV technology. As the VRV technology was new to Sri Lanka at that time, project team had analyzed the option of VRV technology thoroughly than other two options. They have considered both the water cooled and air cooled options for the condenser side of the system. Though the water cooled system is inherently efficient than the air cooled system of respective air-conditioner system, project team had decided to overlook that option as there were no successful air cooled VRV air-conditioning system installed in Sri Lanka to consider as a reference project. Also, all the suppliers had advised the project team not to select the water cooled option if the Central Bank wants to install a VRV air-conditioning system. Therefore, the project team had finally decided to consider only the air cooled option under the VRV technology. The advantages and disadvantages that the project team had identified under the VRV option are as follows.

Advantages: In the VRV system, there won't be a problem with regard to the appearance of the building as there will be only few outdoor units to be installed outside the building. Unlike in the case of the split air-conditioner system, those outdoor units could be installed at a remote location like the backyard of the building without disturbing the appearance of the building. Energy efficiency and part load performance of a VRV air-conditioning system is better than that of chiller air-conditioning system and far better than that of the split type air-conditioner system.

Disadvantages: As the VRV technology is new to Sri Lanka, there were no way to check the reliability, durability, and maintainability of the installations. Installation and maintenance experience of VRV air-conditioning contractors were not satisfactory. In addition, there was a worry about the possibility of total system failure in case of a failure of respective outdoor unit. But, most of the suppliers claimed that this type of situation is unlikely as the outdoor unit comprises of multiple compressors.

After analyzing about the advantages and disadvantages of above three options, the project team compared the advantages and disadvantages of each option with that of the other two options. The project team had given a higher emphasis on the appearance of the building and operating efficiency of the air-conditioning system. As a result of the higher emphasis given to the above two aspects, the project team had given up the split type air-conditioner option despite of its higher flexibility of operation. When analyzing the other two options, the team had realized that both the options are equally favorable with respect to the attributes related to the appearance. Further, with the help of the information obtained from the suppliers of VRV air-conditioners and chillers, they have observed that the operating efficiency of VRV air-conditioning system is better than that of a chiller system. But, they had not obtained the part load efficiency values of these two equipments to arrive at the above observation.

In addition to the appearance and operation efficiency, the project team had looked into the installation restrictions / constraints and maintainability of these systems. They had noted that installation of a chiller air-conditioner system requires more indoor space than the space required for the VRV air-conditioner system. They had also considered that, with the limited ceiling and service space available in the building, laying of insulated Copper pipes is easier than laying of insulated chilled water pipes. Furthermore, the project team had realized that there is a risk of installing a VRV air-conditioning system at the building as it was a new technology for Sri Lanka at that time and hence there was no way to look in to the real operation and maintenance problems of it. However, they have decided to select the VRV option considering the following facts,

- It does not disturb the overall appearance of the building
- It is the best option with regard to the energy efficiency among the three options which were under consideration
- VRV system is the most favorable option with regard to the space constraints.
- Maintainability and reliability wouldn’t be a problem as there are successful project references in other countries where VRV air-conditioning systems have been installed and maintained for a satisfactory period.

As described above, the project team had convinced the management that the most appropriate air-conditioning system for the hostel block of the Center for Banking Studies is a VRV air-conditioning system.

4.2.4 Operation pattern of the system

As described in the previous paragraphs, the hostel block of the Center for Banking Studies was leased to Bandaranaike National Memorial Foundation after the completion of renovation works. The building is now being managed by them as a hotel and they obliged to provide accommodation facilities to the residential training programs conducted by the Center for Banking Studies. According to the lease agreement, Bandaranaike National Memorial Foundation can use the hotel for commercial purposes whenever it is not required for the residential training programs by the Center for Banking Studies.

When the hotel is fully occupied by the participants of the training programs, the participants usually leave the hotel rooms in the morning. Except the participants who return to rooms to take a bath or for some personal requirement during the lunch break, the majority of the participants return to the rooms at the end of the day’s training program. All the participants are going to the restaurant for the dinner, while most of them stay in their rooms till the morning of the following day.

4.3 Maintainability and problems encountered during the operation of the system

4.3.1 Weakening the insulation of refrigerant pipes

As described in the above paragraphs, the insulated copper refrigerant pipes connecting the outdoor units and indoor units have been laid through the ceiling space. The refrigerant pipes are running above the toilets and entrance lobby of the rooms. After about two year operation, the maintenance personnel had observed some occasional wet patches on the ceiling of toilets. Further they had observed the frequency of appearing the patches and wetness of the patches were increasing with time. So, the maintenance team has suspected that the patches are due to the leaking of water from the sanitary plumbing network or weakening of the waterproofing of the toilet slab of the above floor. Accordingly, they had opened the ceilings of toilets where wet patches were observed more frequently and inspected the pipes and soffit area above the ceiling. Then they have observed that there are condensate water droplets on the insulation of the refrigerant pipes. The insulation of the refrigerant pipes had weakened and condensation had formed on the surface of the insulation. When the reason for this condition was analyzed it had been revealed that the density of used insulation is not adequate for this installation. The density of insulation they have used is 50 kg/ m3. The maintenance department then has decided to replace the insulation of refrigerant pipes with a high quality Closed cell Nitrile Rubber insulation having a density of 70 kg/m3.

In addition to the above problem, there had been some refrigerant leakages during the initial operation of the system. After the repairing of these leakages no significant fault or weakness in the air-conditioner system had been reported. The contractor has maintained the air-conditioning system satisfactorily without major interruptions or breakdowns after the rectification of problems encountered during the initial period of operation.

4.3.2 Tenant's concerns regarding the VRV system

After the rectification of faults and defects encountered during the initial operation of the air-conditioning system, and once the system started to operate smoothly, the tenant has not complained about the operation and maintenance problems of the system. But after about three years, they had raised a concern regarding the energy consumption of the air-conditioning system. Their major concern was on the necessity of the operation of a large outdoor unit of the air-conditioning system whenever at least one indoor unit connected with the respective outdoor unit is in operation. They complained that even when a single room is occupied it is required to operate an outdoor unit which has a capacity to operate about 12 nos of indoor units. Though the management of the Center for Banking had taken a keen effort to explain the tenant regarding the operation of VRV system and the way it operates under the part load conditions, the tenant had repeatedly complained about this situation and ultimately proposed to replace the VRV air-conditioning system with split type air-conditioners.

In order to sort-out this controversial situation, the management of Center for Banking Studies had proposed to conduct an Energy Audit at the building through a reputed organization acceptable to both the parties. Accordingly, the National Engineering Research and Development Center has carried out an energy audit at the Sovereign Residencies. From the findings of the Energy Audit, the management of the Center for Banking Studies has convinced the management of Sovereign Residencies that the impression they had regarding the high energy consumption of the existing VRV air-conditioning system was not correct. Details about the Energy Audit are explained in 4.4.1 below.

4.4 Energy efficiency of the installed air- conditioning system

Though the VRV air-conditioning system believed to be a highly efficient air conditioning system, after handing over the building the management of the Sovereign Residencies had requested to replace it with a split type air-conditioners as the VRV air-conditioning system is not efficient for their usage. To resolve this problem an Energy Audit was carried out by the National Engineering Research and Development Center. This research study critically evaluated the approach and the outcome of the energy audit to check whether it can validate the prevailing favorable attitude on the outstanding energy performance of the VRV air-conditioners. Further, a computer simulations for the building were performed based on each considered potentially applicable air-conditioning system to ascertain the comparative energy performance of them.

4.4.1 Scope and Findings of the Energy Audit

This energy audit had performed to analyze the present status of energy usage in hotel, share of monthly energy consumption by each end user, identify the important energy cost centers, the potential energy conservation opportunities in particular areas. Further, this study had focused to analyze the performance of existing VRV air conditioning system and economic viability of introducing individual split type air conditioners to the rooms instead of existing VRV multi split air-conditioning systems.

Energy audit had revealed that the VRV air conditioning system installed at the Sovereign Hotel consumes around 40% of total hotel electricity consumption. According to the system set up, each out door units has connected 10- 12 number of indoor units (rooms) and therefore those out door units have to be operated, even though a single room; that connected to the particular out door unit, is occupied. As the hotel management was of the view, it may not be economical to operate such type of high capacity out door unit with less number of indoor units (1, 2, 3 or 4).

Basically the room reservations were based on the customers' preference and the hotel staff didn't allocate particular room/ rooms according to their schedules. Therefore the hotel management had an intension of introducing individual split type air conditioning units to rooms. Management of the CBSL had requested the auditor to analyze and comment on this situation in the audit report. In this relation, the auditors had tried to analyze the performance (power consumption) of existing out door units for different load settings (part load calculations) and then compare with the proposed systems.

Accordingly, two numbers of outdoor units with different capacities had been tested individually by isolating (switching off indoor units) single room per time. The selected low capacity and high capacity out door units were belongs to room numbers 301- 310 and 212- 222 A & 222B respectively. The electrical power drawn by each system had been separately monitored (10- 15 minutes intervals) for each load setting. The summarized power consumption data with different indoor unit combinations are given in table 3.

According to the table 3, auditor had highlighted that each outdoor unit had consumed less than 4.0 kW until 4 numbers of indoor units were connected. Also, it had been observed that the energy consumed by outdoor units to produce a unit of cooling (Energy Efficiency Ratio) had been gradually decreasing while switching off the indoor units. Further, the power consumptions of each system; with a single room operation, was almost 2.4 KW and the auditor had stated that this power consumption was slightly higher than the power consumption of a split type air-conditioner required for the same room. The comparisons of power consumption of existing air-conditioning system and the proposed individual split type air-conditioning system are given in the table 4.0. Using the values in table 4.0, the auditor had concluded that the existing system is highly economical than a split type air conditioning system when more than 4 units are operated.

Based on the values in table 4, auditor had highlighted that the power consumption of the air-conditioning system will be doubled, if 18,000 BTU/hr, split type, individual air conditioning units are introduced instead of the existing indoor units at low load conditions (up to four number of rooms operation). Accordingly, the auditor had recommended to use the present AC system to operate even under low load conditions. With the recommendations of the energy audit, the management of CBSL had convinced the tenant that the existing VRV air-conditioning system is the most efficient and economical system for the building.

However, this research study revealed that the auditor had made an inappropriate comparison while arriving at the above conclusion. In the comparison, the auditor had considered that the power capacity of a split type air-conditioner required to replace an indoor unit having a capacity of 9,600 BTU/h of the VRV system as 18,000 BTU/h. This assumption is not reasonable due to following main reasons,

- It compares air-conditioning units of different capacities of two different technologies
- It assumes that at least a split type air-conditioner of 18,000 BTU/h is required to replace the indoor unit of capacity 9,600 BTU/h connected to the existing VRV air-conditioning system. As the existing indoor units of capacity 9,600 BTU/h satisfactorily serves the hotel rooms under all prevailing climatic and operational

conditions, there is no basis of assuming a split type air-conditioner of substantially higher capacity compared to the capacity of existing indoor unit.

- It compares the energy consumption of a VRV air-conditioner system under actual operating condition with the rated energy consumption of a split type air conditioner operating at the rated capacity.

Accordingly, this research study revealed that, though the management of CBSL had convinced the tenant regarding the efficient performance of the existing VRV air-conditioning system using the findings of the energy audit, the audit findings had been made based on some undesirable assumptions.

Common Data Considered for the Estimation and Comparison

Air Conditioners Details

Type	=	split/ wall mounted
Average room size	=	200 ft2- 300 ft2
Selected AC Capacity	=	18000 BTU/h
COP	=	0.75- 0.80 RT/ KW
Air Circulation	=	750- 850 M3/ hr
Rated current	=	9.0- 10.0 A
Rated power	=	1.8- 2.0 KW
Average price	=	75000- 100000 LKR

Table 3 : power consumption with different indoor units operation

Conditions	Operating Room no(s)	Measured Power (kW)
Ground floor (cooling capacity 8RT)		
One room indoor unit operated	310	2.345
Two room indoor unit operated	309-310	2.613
Three room indoor unit operated	308-310	3.115
Four room indoor unit operated	307-310	3.705
Five room indoor unit operated	305 & 307- 310	4.342
Six room indoor unit operated	304,305 & 307- 310	5.212
Seven room indoor unit operated	303- 305 & 307- 310	6.719
Eight room indoor unit operated		
Nine room indoor unit operated	302-310	7.062
Ten room indoor unit operated	301-310	7.142
Second floor (cooling capacity 12RT)		
One room indoor unit operated	212	2.399
Two room indoor unit operated	222 A & 222 B	2.452
Three room indoor unit operated	221- 222 B	2.518
Four room indoor unit operated	220- 222 B	3.041
Five room indoor unit operated	219- 222 B	3.715
Six room indoor unit operated	218-222 B	4.075
Seven room indoor unit operated	217- 222 B	5.241
Eight room indoor unit operated	216- 222 B	6.627
Nine room indoor unit operated	215-222 B	7.592
Ten room indoor unit operated	214- 222 B	8.142
Eleven room indoor unit operated	213- 222 B	9.266
Towel room indoor unit operated	212-222 B	10.616

Table 4 : Consumption of power consumption of existing system and split AC units

Conditions	Operating Room no(s)	Rated power	
		Existing system kW	Individual Split kW
Ground floor (cooling capacity 8RT)			
One room indoor unit operated	310	2.613	2.0
Two room indoor unit operated	309-310	2.345	4.0
Three room indoor unit operated	308-310	3.115	6.0
Four room indoor unit operated	307-310	3.705	8.0
Second floor (cooling capacity 12RT)			
One room indoor unit operated	212	2.399	2.0
Two room indoor unit operated	222 A &	2.452	4.0
Three room indoor unit operated	221-222 B	2.518	6.0
Four room indoor unit operated	226-222 B	3.041	8.0

4.4.2 Computer simulation on different options of air-conditioning systems

An Equest computer simulation was carried out to study the performance of split, VRV and Chiller air-conditioner systems with respect to this building.

4.4.2.1 Building Modeling

The building shape is roughly rectangle and all the rooms are placed sides of the building. The middle area of the building is a void open to the sky. The building ground level plan layout is shown in figure 07.

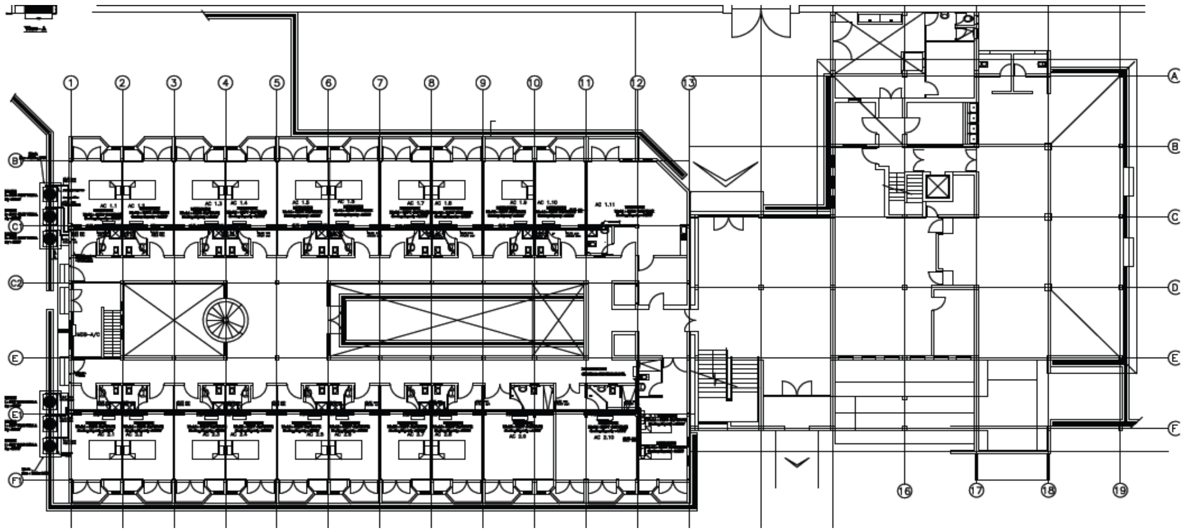

Figure 5 : Building ground floor plan

A 3D computer model of the complete three storied building was created using actual dimensions and material properties of the building and windows. The 3D model of the building and zoning arrangement are shown in figure 8 and figure 9 respectively.

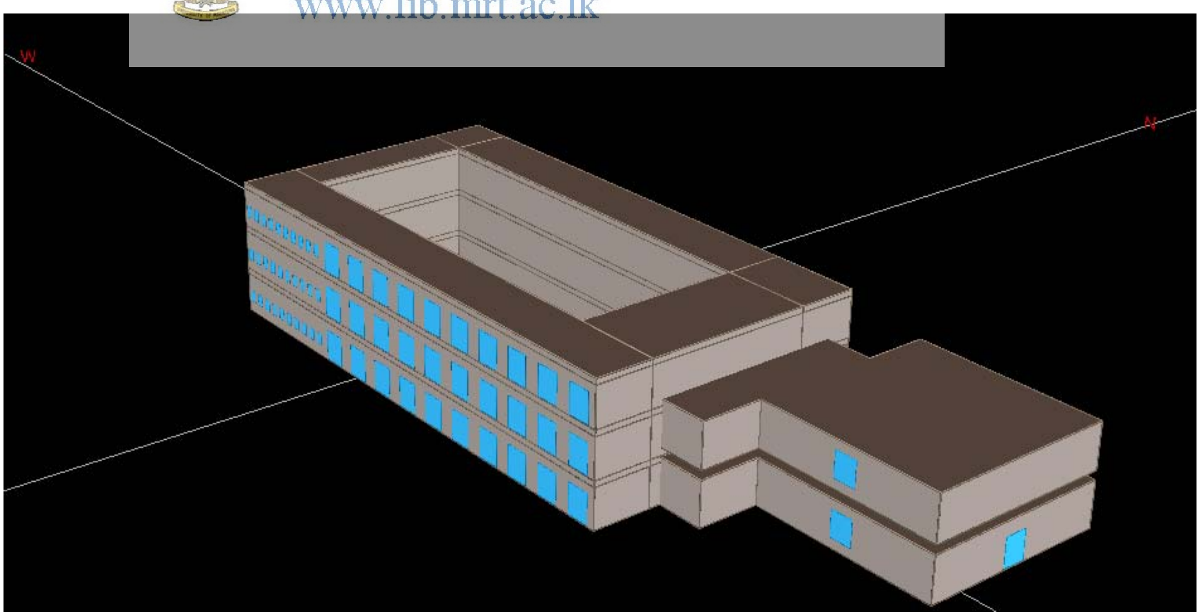

Figure 6 : Building 3D model

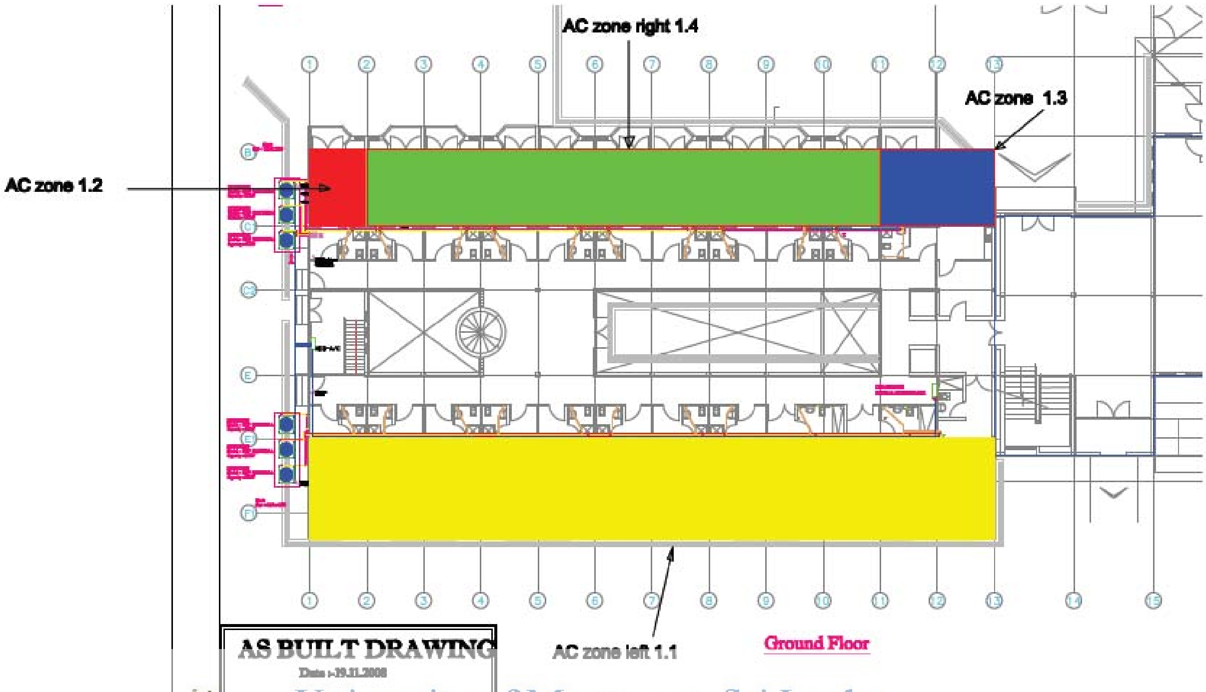

Figure 7 : Building zoning arrangement

The effective plug loads of the buildings were calculated based on the available actual equipment loads and reasonable diversity factors. Summary of appliance and lighting load of the building is shown in the following table.

Table 5 : Summary of appliance and lighting load

Central Bank - Rajagiriya																	
Floor name	Space actual name	Area, ft2	Light loads	No of small rooms	No of large rooms	Total light loads W	Area %	Diversity factor	Light density	Machine load CCTV	Machine load electric kettle	Diversity for CCTV	Diversity for electric kettle	Total machine load	Machine density	Set temperature C	No of people
Ground	AC rooms left 1.1	1806	14W CFL Nos 05 Fluorescent 36W Nos 01 60W spot lamp 01	10	2	1992	50%	0.5	0.551	636	12000	0.25	0.08	1119	0.620	24	26
	AC rooms 1.2	150.5	15W CFL Nos 05 Fluorescent 36W Nos 01 60W spot lamp 01	1	0	166	4%	0.5	0.551	53	1000	0.25	0.08	93.25	0.620	24	2
	AC rooms 1.3	301	16W CFL Nos 05 Fluorescent 36W Nos 01 60W spot lamp 01	0	2	332	8%	0.5	0.551	106	2000	0.25	0.08	186.5	0.620	24	6
	AC rooms right 1.4	1354.5	17W CFL Nos 05 Fluorescent 36W Nos 01 60W spot lamp 01	9	0	1494	38%	0.5	0.551	477	9000	0.25	0.08	839.25	0.620	24	18
First	AC rooms left 2.1	1806	18W CFL Nos 05 Fluorescent 36W Nos 01 60W spot lamp 01	10	2	1992	50%	0.5	0.551	636	12000	0.25	0.08	1119	0.620	24	26
	AC rooms 2.2	150.5	19W CFL Nos 05 Fluorescent 36W Nos 01 60W spot lamp 01	1	0	166	4%	0.5	0.551	53	1000	0.25	0.08	93.25	0.620	24	2
	AC rooms 2.3	301	20W CFL Nos 05 Fluorescent 36W Nos 01 60W spot lamp 01	0	2	332	8%	0.5	0.551	106	2000	0.25	0.08	186.5	0.620	24	6
	AC rooms right 2.4	1354.5	19W CFL Nos 05 Fluorescent 36W Nos 01 60W spot lamp 01	9	0	1494	38%	0.5	0.551	477	9000	0.25	0.08	839.25	0.620	24	18
Second	AC rooms left 3.1	1806	20W CFL Nos 05 Fluorescent 36W Nos 01 60W spot lamp 01	10	2	1992	50%	0.5	0.551	636	12000	0.25	0.08	1119	0.620	24	26
	AC rooms 3.2	150.5	21W CFL Nos 05 Fluorescent 36W Nos 01 60W spot lamp 01	1	0	166	8%	0.5	0.551	53	1000	0.25	0.08	93.25	0.620	24	2
	AC rooms 3.3	301	22W CFL Nos 05 Fluorescent 36W Nos 01 60W spot lamp 01	0	2	332	18%	0.5	0.551	106	2000	0.25	0.08	186.5	0.620	24	6
	AC rooms right 3.4	1354.5	21W CFL Nos 05 Fluorescent 36W Nos 01 60W spot lamp 01	9	0	1494	38%	0.5	0.551	477	9000	0.25	0.08	839.25	0.620	24	18

Climatic Data

Climate data for a typical meteorological year (TMY) based on proximity, climate data for Colombo - Katunayake was used for the simulation. The temperature set point for the building was used as 24oC.

Schedules

The selected building is managed by a hotel management company as a hotel and they have to provide accommodation facilities to the residential training programs conducted by the Center for Banking Studies. With the provisions available in the lease agreement, the management company uses the hotel for commercial purposes whenever it is not required for the residential training programs by the Center for Banking Studies. Accordingly, casual guests are allowed when there is no training program and when the building is not fully occupied by the participants of training programs.

When the hotel is occupied by the participants of the training programs, the participants usually leave the hotel rooms and assembling at the training center (Center for Banking Studies which is located adjacent to the hotel) in the morning. Except the participants who return to rooms to take a bath or for some personal requirement during the lunch break, the majority of the participants return to the rooms at the end of the day's training program. Usually, all the participants get the dinner from the hotel restaurant and most of them stay in their rooms till the morning of the following day. Considering the above explained usual routing nature of the occupancy pattern of the hotel, the following occupancy and cooling schedule was developed for the simulation.

Schedule of occupancy

Night stay : 6.30 pm to 7.30 am following day (occupancy depends on the training programme)

Lunch break : during 11.30 am to 2.00 pm of the day time75% of the participants return to rooms during the lunch break

Occupancy, fan and cooling schedule is summarized in the following table

Table 6 : Schedule of occupancy, fan and cooling

Time	Occupancy Schedule	Fan Schedule	Cooling Schedule (^{0}C)
24 – 01 hrs	1	1	24
01 – 02 hrs	1	1	24
02 – 03 hrs	1	1	24
03 – 04 hrs	1	1	24
04 – 05 hrs	1	1	24
05 – 06 hrs	1	1	24
06 – 07 hrs	1	1	24
07 – 08 hrs	1	1	24
08 – 09 hrs	0.6	1	24
09 – 10 hrs	0.6	1	24
10 – 11 hrs	0.6	1	24
11 – 12 hrs	0.6	1	24
12 – 13 hrs	0.75	1	24
13 – 14 hrs	0.75	1	24
14 – 15 hrs	0.6	1	24
15 – 16 hrs	0.6	1	24
16 – 17 hrs	0.6	1	24
17 – 18 hrs	1	1	24
18 – 19 hrs	1	1	24
19 – 20 hrs	1	1	24
20 – 21 hrs	1	1	24
21 – 22 hrs	1	1	24
22 – 23 hrs	1	1	24
23 – 24 hrs	1	1	24

4.4.2.2 Simulation for Chiller Air-conditioning System

For the simulation of building air-conditioning system on the chiller model, chiller capacity and COP of the chiller were considered as 70 TR and 5.5 respectively. Using these data, the building air-conditioning system was simulated on the above model for a chiller system. Outcome of the simulation is as follows.

Monthly Energy Consumption of the chiller

Energy consumption of chiller for the twelve months of the year are shown in the following chart

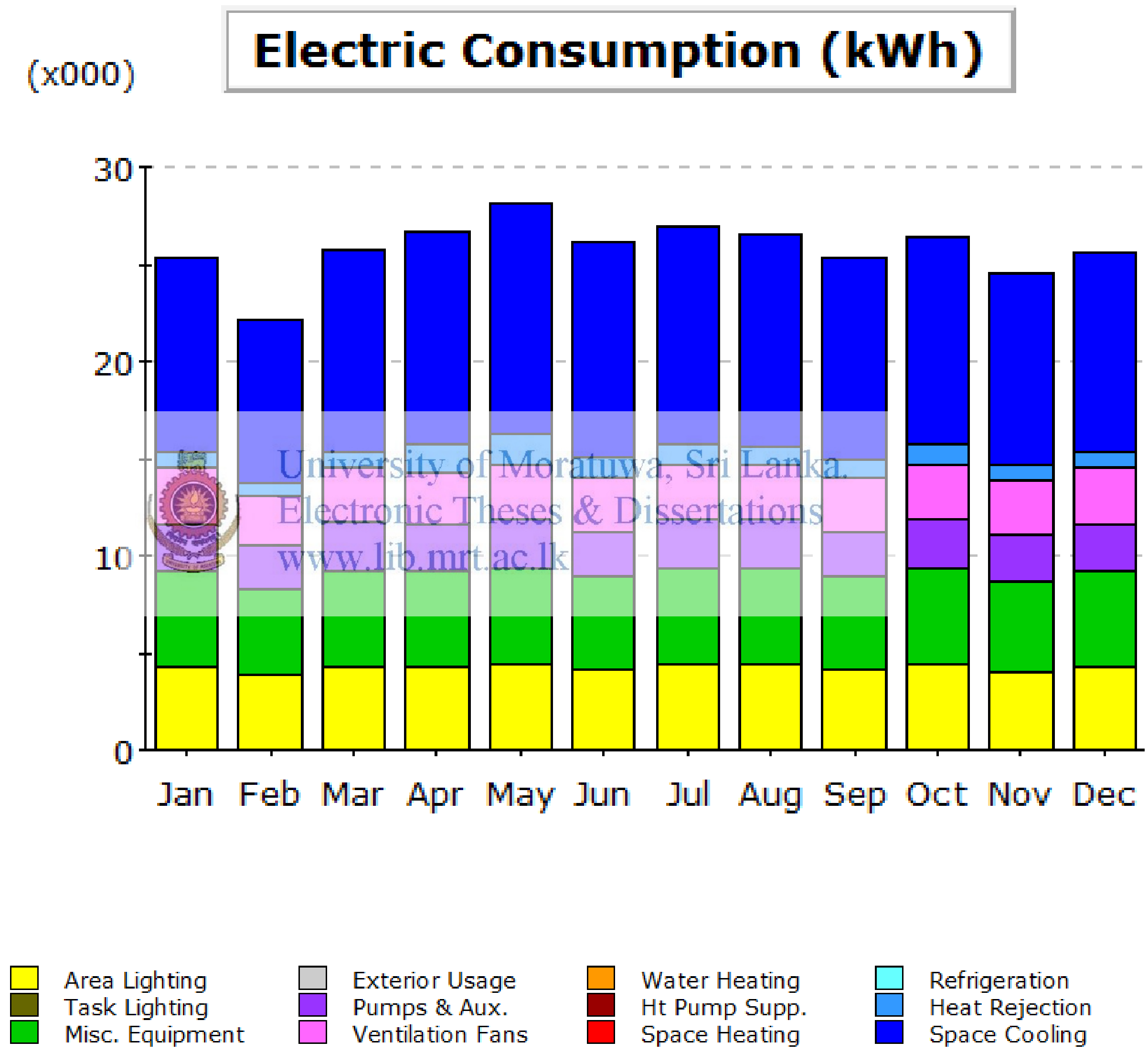

Figure 8 : Monthly energy consumption of chiller

Chiller load profile

Chiller load profile corresponding to the established building model and assumed equipment capacity / efficiency is as follows.

Table 7 : Chiller operating hours in different loading conditions

Part load calculation												
No of hours each part load	Chiller 01											
Month	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100+	Total run hrs
January	0	11	32	118	179	152	140	93	19	0	0	744
February	8	2	36	134	174	116	120	79	3	0	0	672
March	0	0	9	80	216	167	157	115	0	0	0	744
April	0	0	2	10	187	198	159	140	24	0	0	720
May	0	1	6	16	83	256	185	141	56	0	0	744
June	0	0	0	15	148	261	168	116	12	0	0	720
July	0	7	2	16	123	297	185	113	1	0	0	744
August	0	0	0	27	163	290	181	83	0	0	0	744
September	0	2	6	25	215	231	159	82	0	0	0	720
October	0	8	5	46	219	187	167	105	6	1	0	744
November	0	15	5	72	226	167	131	97	7	0	0	720
December	0	7	19	93	229	138	131	121	6	0	0	744
Year sum	8	53	122	652	2162	2460	1883	1285	134	1	0	8760
% of hours	0.1%	0.6%	1.4%	7.4%	24.7%	28.1%	21.5%	14.7%	1.5%	0.0%	0.0%	100.0 %

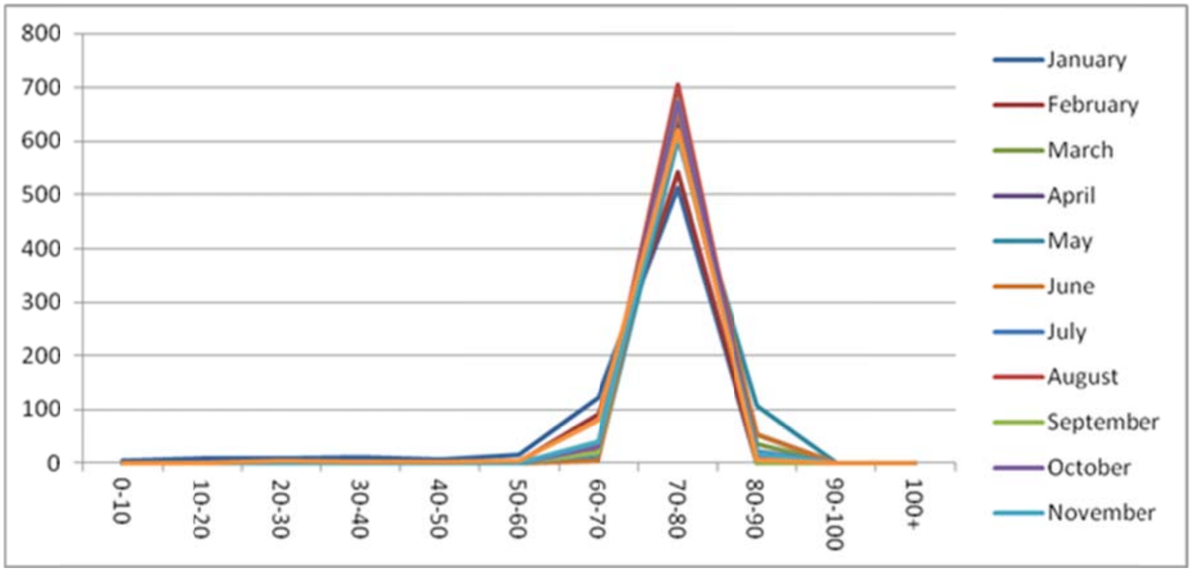

Figure 9 : Chiller load profile for each month

Hourly load profile of an average day for each month of the year is shown in the following table.

Table 8 : Hourly load profile of the chiller for a day of each month

Month No	Month/Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	January	18.7	17.5	16.7	15.6	15.0	14.1	14.1	13.3	15.2	17.2	22.3	26.9	29.4	32.2	34.5	34.8	34.8	37.1	37.6	34.0	31.1	27.7	24.9	23.2
2	February	20.6	19.6	18.8	18.6	18.2	17.6	16.9	17.1	18.3	21.3	23.6	26.6	28.6	31.8	33.1	33.2	31.9	32.6	30.5	28.9	27.7	25.2	23.0	21.4
3	March	23.3	22.0	20.9	20.9	19.8	19.3	19.8	21.6	23.0	23.0	23.9	25.3	29.0	32.0	34.0	34.0	33.5	34.1	31.6	29.3	27.4	25.0	23.2	21.7
4	April	26.8	26.4	26.9	27.6	27.1	27.0	27.6	28.8	29.5	32.2	34.5	36.5	38.6	40.5	41.1	40.1	39.3	39.2	36.7	34.5	32.6	30.8	29.1	28.1
5	May	25.7	25.8	27.0	28.5	27.6	27.0	28.2	30.0	32.1	33.7	37.1	39.7	41.3	42.3	41.3	40.6	39.4	38.5	36.0	34.2	33.3	30.8	28.5	27.1
6	June	20.4	19.7	19.7	19.4	19.1	18.9	19.7	20.9	21.4	25.2	27.3	29.4	30.3	31.7	29.7	30.5	30.2	30.4	28.5	26.9	25.8	25.1	24.1	23.8
7	July	26.3	26.9	26.8	28.5	28.1	27.5	28.0	29.0	30.4	33.0	34.8	36.2	38.4	39.3	38.6	37.9	37.2	37.2	35.1	33.5	32.6	30.6	28.9	28.0
8	August	22.7	22.2	22.4	23.0	22.7	22.6	22.2	24.0	25.3	28.8	32.1	35.1	37.2	38.6	38.8	38.2	36.4	35.9	34.2	32.8	30.8	29.7	28.8	26.9
9	September	19.5	19.1	18.9	18.7	18.4	18.3	18.6	19.9	20.3	22.3	23.8	27.0	28.3	27.3	27.6	26.6	26.4	26.1	24.3	22.8	21.9	21.1	21.1	20.7
10	October	31.7	31.8	30.9	30.6	29.3	29.7	31.1	32.2	32.1	34.0	36.3	36.7	38.9	40.2	39.5	39.2	37.9	33.7	32.4	31.2	30.9	29.3	28.0	28.5
11	November	24.2	23.9	24.1	23.8	23.4	23.1	23.1	25.1	27.6	30.3	32.8	34.3	38.2	37.9	38.7	38.4	37.5	36.9	34.0	32.3	31.0	28.7	26.4	25.3
12	December	11.9	13.4	15.6	14.8	13.9	13.4	13.5	15.8	17.7	20.4	23.6	26.7	29.9	31.6	32.6	33.0	32.3	32.4	29.1	27.2	25.9	24.6	23.6	22.7

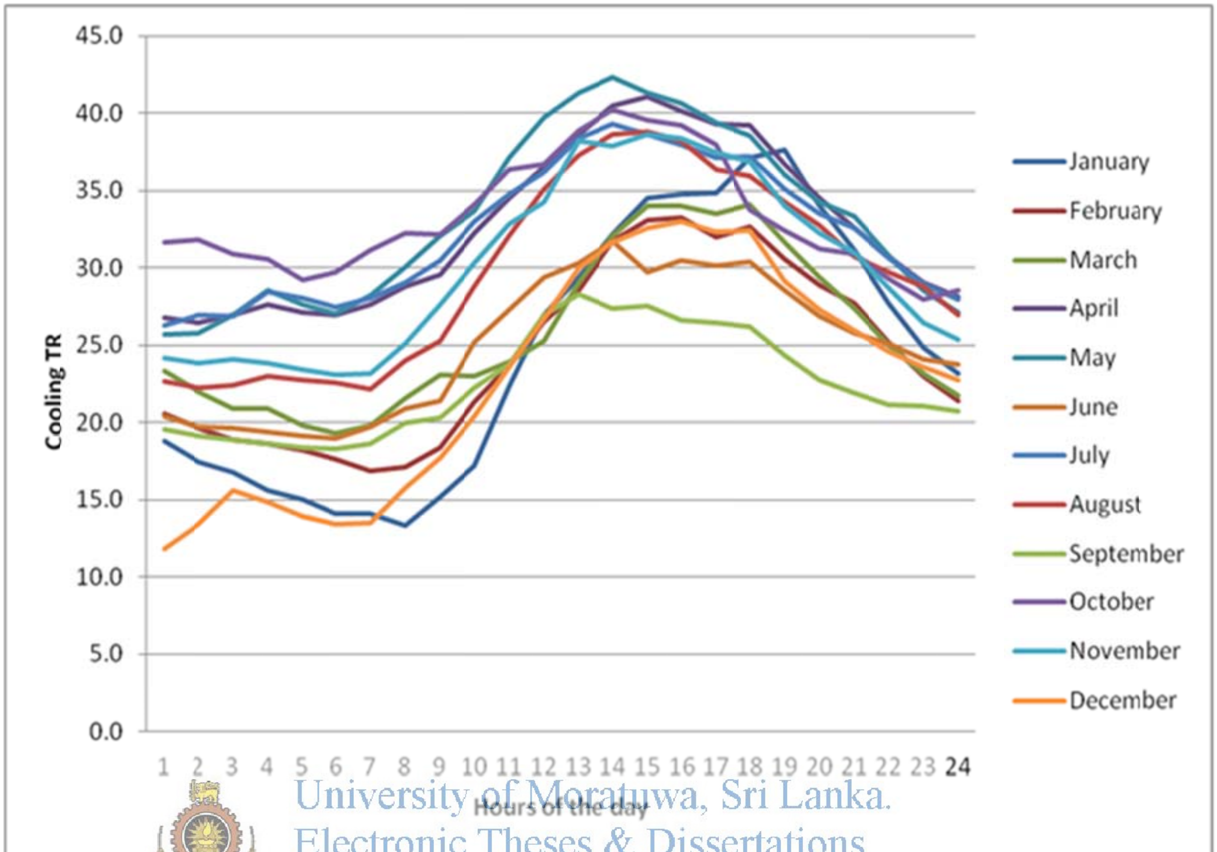

Figure 10 : Hourly load profile of the chiller for a day of each month

4.4.2.3 Simulation for VRV and Split Air-conditioning Systems and Comparison of Energy Performances

The same building model was simulated for VRV and Split type air-conditioning systems with the COP of 3.5 and 2.7 respectively. Comparison of monthly energy consumption of each system is given in the following charts.

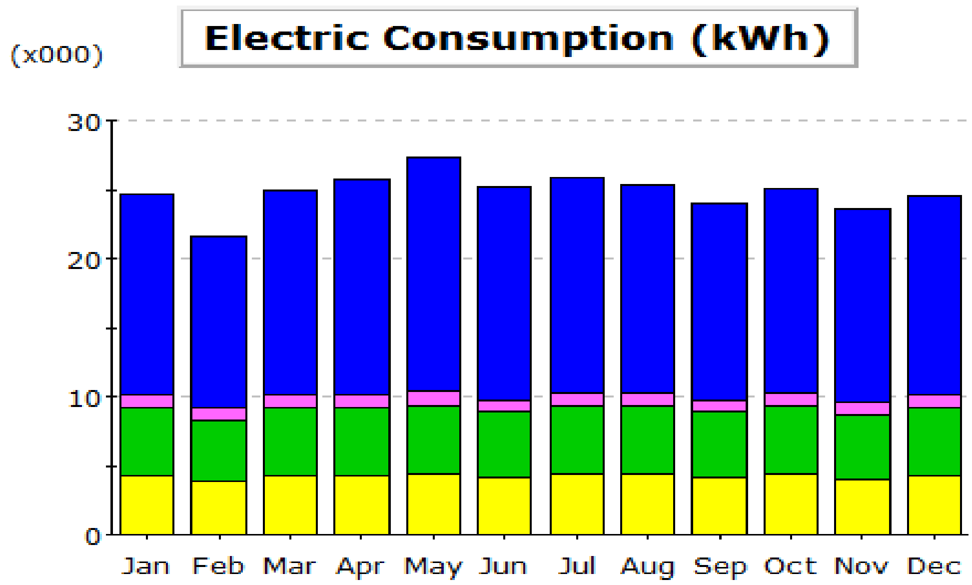

Figure 11 : Monthly energy consumption of VRV Type air-conditioning system

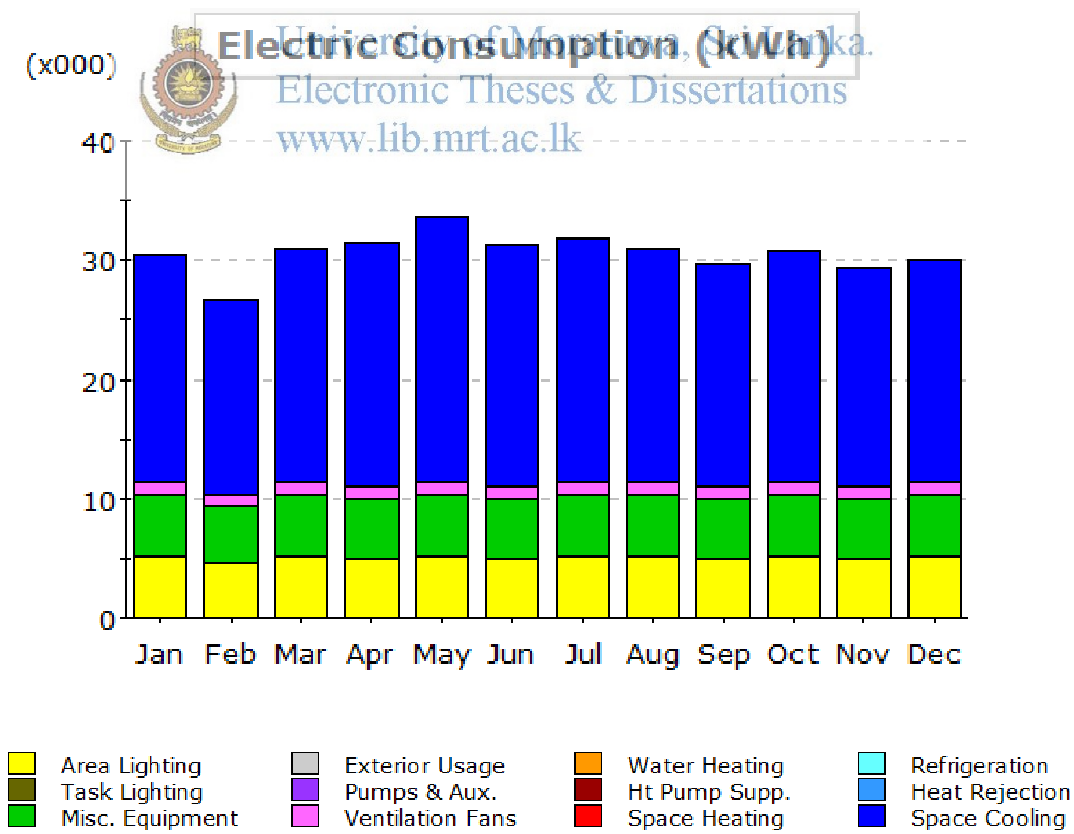

Figure 12 : Monthly energy consumption of Split Type air-conditioning system

4.4.2.4 Comparison of actual energy consumption records with the simulation results of the existing VRV air-conditioning system

Before the comparison and analysis of simulation results of considered air-conditioning systems, it is vital to compare the actual electricity consumption records of the building with the simulation results of the existing VRV air-conditioning system. As the Equest simulation has been performed only for the apartment block (hotel room area) and electricity bills have been issued for the electricity use of the entire building, it was not possible to directly compare the simulation results with the electricity billing data. However, it was possible to separate the total electricity consumption into different areas of the building with the use of information presented in the energy audit report regarding the contribution of each main area of the building to the total energy use. This data can be considered as reasonably accurate as it had been established using the logged data of actual consumption pattern. Comparison of the electricity use records and simulation results are shown in the following table. Calculations are shown in Annexure C.

Table 9 : Comparison of electricity billing data with the simulation results of VRV system

Month	Electricity consumption (kWh)		Deviation		Remarks
	Based on billing data	Based on Equest simulation	kWh	%	
January	24,648	25,790	1142.2	4.6	
February	23,269	22,600	-669.3	-2.9	
March	24,320	26,100	1780.4	7.3	
April	24,956	26,530	1573.7	6.3	
May	25,917	28,310	2393.0	9.2	High deviation
June	23,960	26,340	2380.4	9.9	High deviation
July	26,211	26,850	638.5	2.4	
August	25,033	26,260	1227.0	4.9	
September	24,957	25,110	152.5	0.6	
October	27,954	26,020	-1933.6	-6.9	
November	25,694	24,850	-843.8	-3.3	
December	25,131	25,650	519.1	2.1	

According to the above table, the monthly energy consumption obtained from simulation does not deviate beyond 10 % from the energy consumption estimated based on the electricity bills for all the months though shown high deviations in May and June. This deviation might have been caused due to the irregular occupancy levels during those months in some of the years and changes in percentage of total energy consumption by other end uses. (End use percentages indicated in the energy audit report has been used to apportion the total actual energy consumption among the different end uses.). Other than those two months, results of simulation are reasonably in line with the actual energy use records.

4.4.2.5 Comparison and Analysis of the Monthly Energy Consumption of Chiller, VRV and Split Type Air-conditioning Systems

The outcome of the simulation of chiller, VRV and Split type air-conditioning system on the building model is summarized and tabulated in the following table.

Table 10 : Comparison of monthly energy consumption of Chiller, VRV & Split type air-conditioning systems

Electric Consumption (kWh *000)														
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space cool	VRV	14.47	12.45	14.87	15.57	16.95	15.44	15.60	15.04	14.31	14.80	14.01	14.35	177.86
	Chiller	9.99	8.46	10.31	11.01	11.88	10.98	11.21	10.95	10.38	10.74	9.95	10.23	126.09
	Split	19.04	16.45	19.57	20.42	22.25	20.29	20.41	19.65	18.71	19.31	18.33	18.78	233.21
Heat reject	VRV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Chiller	0.79	0.59	0.87	1.38	1.61	1.11	1.09	0.97	0.96	1.02	0.83	0.81	12.03
	Split	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vent fan	VRV	0.98	0.82	0.89	0.92	1.00	0.91	0.89	0.86	0.81	0.86	0.87	0.96	10.77
	Chiller	2.85	2.58	2.85	2.76	2.85	2.76	2.85	2.85	2.76	2.85	2.76	2.85	33.57
	Split	1.02	0.92	1.02	0.99	1.02	0.99	1.02	1.02	0.99	1.02	0.99	1.02	12.02
Pump & Aux	VRV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Chiller	2.44	2.20	2.43	2.36	2.44	2.36	2.44	2.44	2.36	2.44	2.36	2.44	28.71
	Split	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Misc. Equipment	VRV	5.14	4.64	5.14	5.01	5.16	4.96	5.16	5.16	4.96	5.16	4.94	5.14	60.57
	Chiller	5.14	4.64	5.14	5.01	5.16	4.96	5.16	5.16	4.96	5.16	4.94	5.14	60.57
	Split	5.14	4.64	5.14	5.01	5.16	4.96	5.16	5.16	4.96	5.16	4.94	5.14	60.57
Area lights	VRV	5.20	4.69	5.20	5.03	5.20	5.03	5.20	5.20	5.03	5.20	5.03	5.20	61.21
	Chiller	5.20	4.69	5.20	5.03	5.20	5.03	5.20	5.20	5.03	5.20	5.03	5.20	61.21
	Split	5.20	4.69	5.20	5.03	5.20	5.03	5.20	5.20	5.03	5.20	5.03	5.20	61.21
Total	VRV	25.79	22.60	26.10	26.53	28.31	26.34	26.85	26.26	25.11	26.02	24.85	25.65	310.41
	Chiller	26.41	23.16	26.80	27.55	29.14	27.20	27.95	27.57	26.45	27.41	25.87	26.67	322.18
	Split	30.40	26.70	30.93	31.45	33.63	31.27	31.79	31.03	29.69	30.69	29.29	30.14	367.01

Variation of monthly energy consumption of above three systems throughout the year is shown in the following figure.

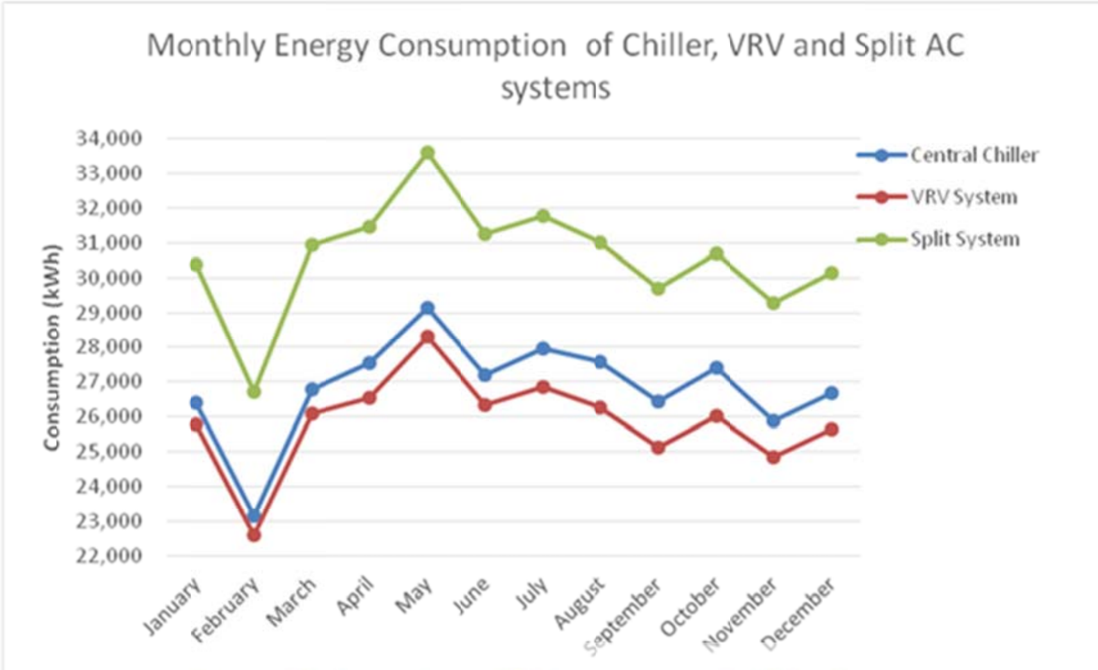

Figure 13 : Monthly energy consumption of Chiller, VRV and Split Type air-conditioning systems

From the above comparison, it was observed that for all the month of the year, monthly energy consumption of the VRV air-conditioning system is tower than that of Chiller and Split type air-conditioning systems. When the monthly energy consumption of Chiller and Split type air-conditioning systems are compared, it was observed that the monthly energy consumption of Chiller air-conditioning system is lower than that of Split type air-conditioning system for all the months of the year. When the total annual energy consumption of these three systems are compared, the lowest energy consumption of 310.41 MWh was resulted from the VRV air conditioning system. The second lowers energy consumption of 323.18 MWh was resulted from the Chiller (central) air-conditioning system and it was 4.1% higher than the annual energy consumption of VRV air-conditioning system. The highest energy consumption of 367.01 MWh was resulted from the Split Type air-conditioning system and it was 18.2 % higher than the annual energy consumption of VRV air-conditioning system. It was also observed that the estimated annual energy consumption of Split Type air-conditioning system is 13.5 % higher than that of Chiller air-conditioning system.

4.5 Life cycle cost analysis of the potentially applicable air- conditioning systems

From the outcome of computer simulation, it was observed that the most efficient and low energy consuming air-conditioning system for the selected building is the VRV air-conditioning system. But, it gives an indication only about the recurrent or operational cost of the potential air-conditioning systems which have been considered for the installation. However, under the introduction, it was discussed that the initial cost and the cost of maintenance could also influence the selection decision of the suitable air-conditioning system for a building. The literature review also envisages that, initial cost of certain air-conditioning technologies, specially the cost of VRV air-conditioners critically affecting on the economic viability of air-conditioners with those technologies. Therefore, it is vital to analyze the life cycle cost of potentially applicable air-conditioning systems before making the final selection decision. Considering that fact, life cycle cost analyses were performed for all three potentially applicable air-conditioning systems for this building.

4.5.1 Estimation of Life cycle cost

Chiller (Central) Air-conditioning System

For the life cycle cost analysis of the central chiller air-conditioning system, following assumptions were made base on the prevailing market conditions, electricity tariff structure and other practical circumstances.

System description:

Type of chiller: water cooled screw type chiller (the same system which was considered for simulation.

Capacity of chiller : 70 TR

Capacity of Fan Coil Units : 0.8 TR

Initial Cost (IC):

Initial cost (cost of installation) of a water cooled screw type average quality central chiller air-conditioning system was considered as Rs. 275,000.00 per TR based on the market sources. This figure was validated from the bid prices of the tenders called recently for the systems of similar nature.

Electricity tariff:

Tariff category HP -1 was considered.

Tariff rate for energy (T) : Rs. 22.00 / kWh

Annual maintenance cost (AMC):

Cost of a service agreement : Rs. 560,000 / year (Rs. 140,000.00 per quarterly service)

Cost of repairs and spare parts: Rs. 380,000/ year (2 % of the initial cost)

AMC is the total of above two costs.

Life span of the system (LS):

Expected life span of an average central chiller system was considered as 20 years.

Economic life span of 18 yeas was considered for the calculation

Considering the above parameters, the life cycle cost of the central chiller system was computed as follows.

$LCC_{\textbf{(chiller)}} = [\sum_{i=\text{Jan - Dec}} (kWh\mathit{i} \text{ x } T) + AMC] \text{ x } LS + IC$

LCC (chiller) = Rs. 163,972,880.00 for the 15 year life span

(Calculations are shown in Annexure –A)

As the potentially applicable air-conditioning systems considered for the building have different life spans, their LCCs are not comparable. Therefore, overall annual average cost (OAC) of the system was calculated based on the LCC as shown below.

OAC (Chiller) = LCC (chiller) / LS

OAC (chiller) = Rs. 9,109,604.00

Similarly, the LCC and OAC of VRV and Split type air-conditioning systems were also estimated and the results are shown in the following table (details of the calculation are shown in Annexure A).

Table 11 : LCC and OAC of potentially applicable air-conditioning systems

Item	Type of air-conditioning system	LCC (Rs)	OAC (Rs.)	LS
1	Water Cooled Chiller (Central)	163,972,880	9,109,604	18
2	Air cooled VRV	96,042,200	9,604,220	10
3	Split	50,478,100	10,097,420	05

According to the results of the LCC analysis, central chiller air-conditioning system has the best overall economic performance compared to the other two applicable air-conditioning systems. This result shows that even though the VRV air conditioning system performed more efficiently than the central chiller system for the selected building, it's overall economic performance over the lifespan is not as good as that of central chiller air-conditioning system due to its high initial cost.

From the above analysis and literature review, it was observed that VRV air-conditioners, despite of high energy performance fails to be economically competitive with central air-conditioning system due to the high initial cost. Therefore, it is vital to find out the range of initial cost that would make the LCC and OAC of VRV air-conditioning systems economically competitive with the central chiller and split type air-conditioning systems. For this purpose, LCC and OAC of VRV, central chiller and split type air-conditioners were estimated for different initial costs (Rs./TR) and plotted on the same graph as shown below, Detailed calculations are shown in Annexure A.

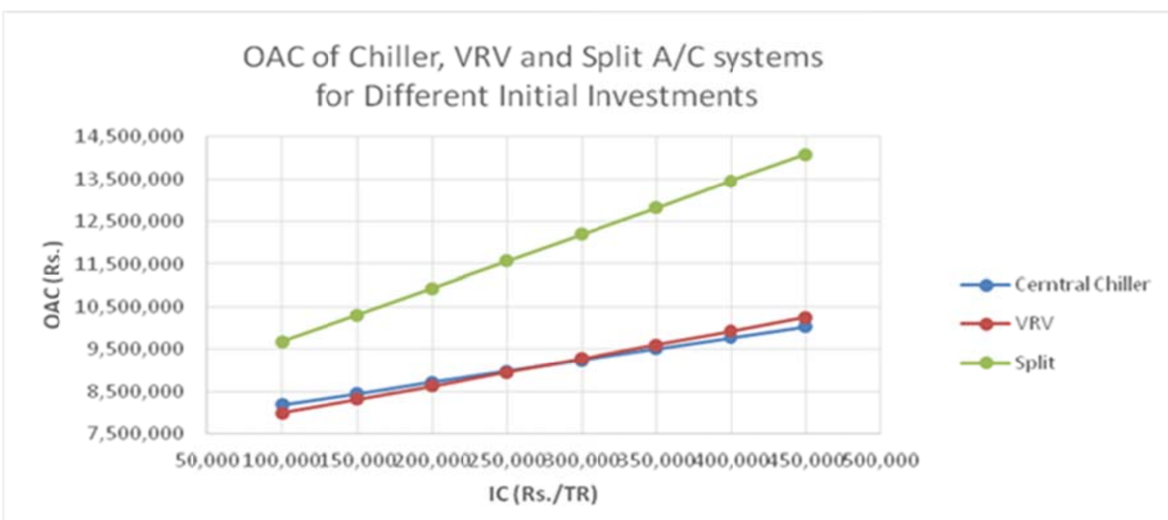

Figure 14 : OAC of potentially applicable air-conditioning systems against initial cost

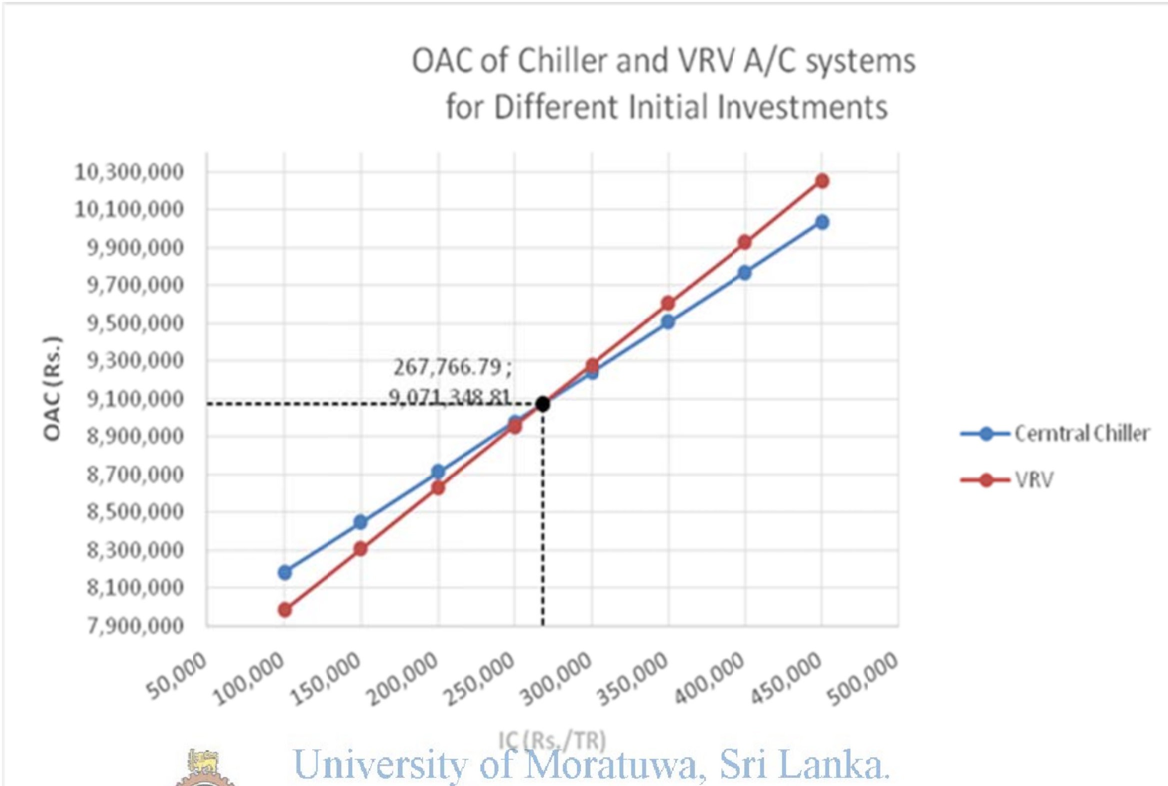

Figure 15 : Economical initial cost of VRV and Chiller air-conditioning systems

The above graph shows that, under the study conditions, VRV air-conditioners become economically attractive when the initial cost of the system go down below Rs. 267,766.79 per TR. When the initial cost increases further, chiller (central) system become economically attractive.

4.5.2 Sensitivity analysis for + 10 % variation of electricity tariff and initial cost.

Sensitivity analysis is important to understand the behavior of LCC against the variation of its dependent variables. Therefore, sensitivity analyses of the LCC of Central Chiller, VRV and Split type air-conditioner systems were performed against the variation of electricity tariff and initial cost by + 10%.

Following figures 16 and 17 show the sensitivity of LCC of above three systems against +10% variations of electricity tariff and initial cost respectively.

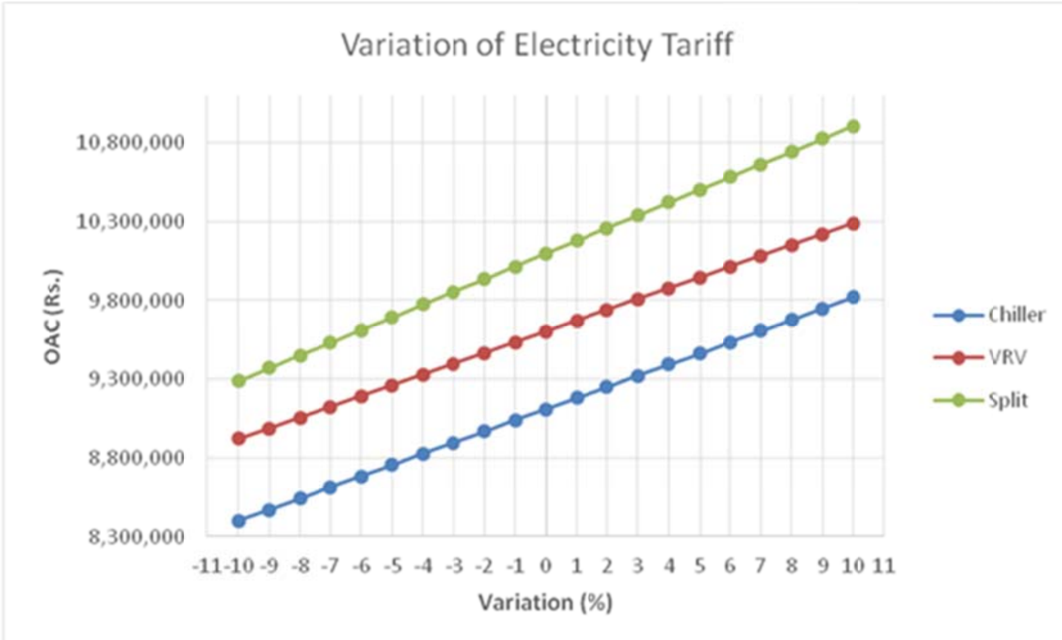

Figure 16 : Sensitivity of OAC of potentially applicable air-conditioning systems against electricity tariff

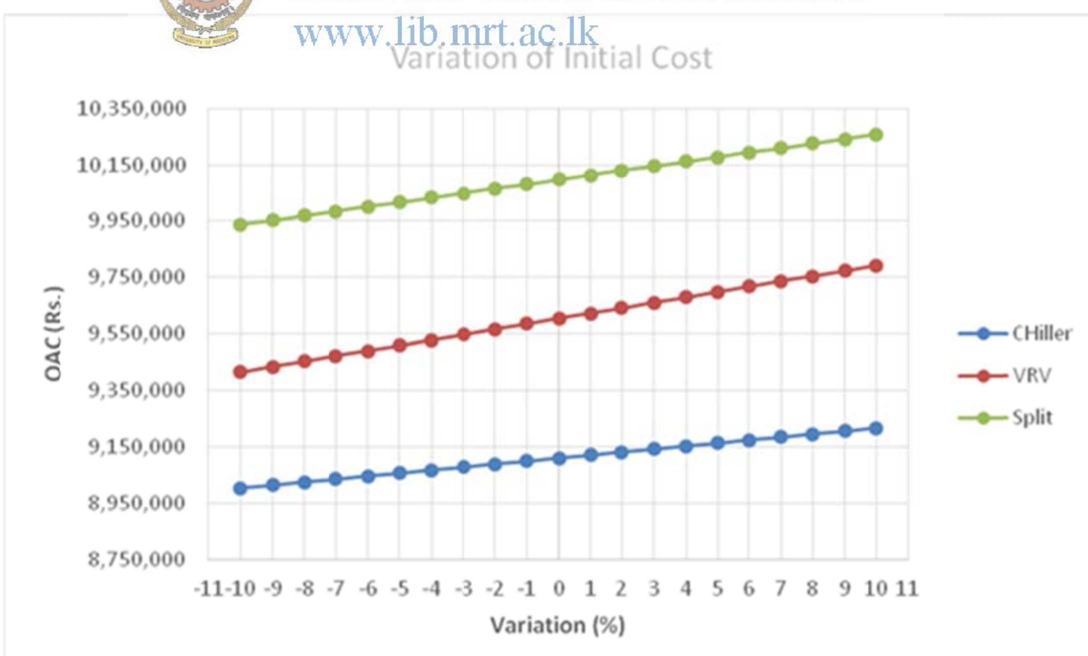

Figure 17 : Sensitivity of OAC of potentially applicable air-conditioning systems against initial cost

Sensitivity analysis for electricity tariff shows that VRV air-conditioning system has the lowest sensitivity to the variation of electricity tariff when compared with the other two systems. Split type air-conditioners shows the highest sensitivity for variation of electricity tariff. VRV, Chiller and Split system show Rs. 68,362.20, Rs. 70,951.60 and Rs. 80,814.20 variations in OAC for a 1.0 % variation of electricity tariff. The same three systems have shown different responses for the variation of initial cost. VRV system which showed the lowest sensitivity to variation of electricity tariff has shown the highest sensitivity to the initial cost. The chiller system has shown the lowest sensitivity for variation of initial cost. Chiller, Split and VRV air-conditioners show Rs. 10,694.44, Rs. 16,000.00 and Rs. 18,900.00 variations in OAC for a 1.0 % variation of initial cost.

CHAPTER 05

Conclusion and Recommendations

5 Conclusion and Recommendations

The main aim of this assignment was to study about the VRV air-conditioning system, its maintainability and analyzing whether the prevailing demand for VRV air-conditioners is because of its ability to satisfy the desires of purchasers. The methodology selected for the study was carrying out a case study in a representative installation to achieve the research objectives. A computer simulation was also performed on EQUEST to compare the energy efficiency of the VRV air-conditioning system against the other alternative air-conditioning systems which were considered for the installation at the preliminary stage of the project (i.e. split type air-conditioners and chiller system).

5.1 Ability of VRV air-conditioners to satisfy the desires of the purchaser

The project team that had been appointed by the CBSL for the implementation and management of renovation project of the selected installation had following desires when selecting the appropriate air-conditioning system for the Sovereign Building (Hostel Block of the Center for Banking Studies then).

- The appropriate air-conditioning system should be suitable for all the possible occupancy patterns of the building. As the building is an accommodation unit which provide accommodation facilities to the participants of the training programs organized by the Center for Banking Studies, the occupancy vary from program to program. For example, it could vary from about 10% to 100%. The air-conditioning system should be operated even when the occupancy is very low. This requirement would have been best satisfied if the project team had selected the split type air-conditioners for the building. But, due to some other constraints related to the external appearance, the project team had not selected the split air-conditioners for the installation. However, with the installed VRV air-conditioning system, the users of the building have successfully provided air-conditioning facilities for all the occupancy conditions they had to cater during the last five years. In that respect, the VRV air-conditioning system has fully satisfied the owner's desire on the ability of operating the air-conditioning system under any occupancy level.
- The air-conditioning system had to be installed in the existing structure which is not designed to accommodate an air-conditioning system. There were restrictions

with regard to the space and headroom required for installation of chiller air-conditioning system for the building. The limited space at the basement was required for the operational services of the building. Installation of insulated chilled water pies and condenser water pipes also was a challenging task with the limited headroom at the basement (just around 2m). Alternatively, the ceiling space available in the room area was sufficient to install insulated refrigerant pipes of the VRV air-conditioning system. The outdoor units of the VRV system could be easily placed in the back yard of the building without any problem. Accordingly, the VRV air-conditioning system could be installed in the building satisfactorily within the available space. Per se the VRV air-conditioning system had satisfied the building owner's requirement of installing the air-conditioning system in an existing building structure despite of the space and structural restrictions.

- The project team had considered three options of air-conditioning systems for the building at the preliminary stage. The alternative options they had considered are split type air-conditioners, Chiller air-conditioning system and VRV air-conditioning system. The team had decided not to further consider split air-conditioner option due to the concern regarding the appearance. This decision was further validate by the low energy efficiency of split type air-conditioners. The project team had considered other two options as equally energy efficient. As both the options were considered as equal in terms of energy efficiency, the project team had decided to select the VRV air-conditioning system. The average efficiency of the installed VRV air conditioners is around 0.65 – 0.75 kW/RT and it is a reasonably justifiable value compared with the efficiency of 0.5 to 0.7 kW/RT of an average chiller. However, the user of the building had raised a concern regarding the disadvantage of operating the outdoor unit of the VRV air-conditioning system even when a single room is occupied. As they do not possess the knowledge about the basic technology of the VRV air-conditioners, they had proposed to replace the existing VRV system with split air-conditioners to conserve electricity. The management of the Center for Banking Studies has somehow convinced the tenant that the available VRV air-conditioning system is the most suitable system of air-conditioning system to the building in terms of Energy Efficiency. Therefore, the VRV system has fulfilled the owner's expectation on Energy Efficiency satisfactorily.

5.2 Computer simulation of different air-conditioning options considered for the building and saving potential of VRV air-conditioners

A computer simulation was performed using equest Energy Simulation tool to compare the energy performance of VRV air-conditioning system with the split type air-conditioners and chiller air-conditioning system which were the other two air-conditioning options considered by the project team during the preliminary stage of the project. Following conclusions were made from the results of simulation.

- The most efficient air-conditioning system for this building is VRV air conditioning system against the other two options namely Chiller and Split type air-conditioning systems. According to the outcome of the simulation, annual energy consumption of VRV, Chiller and Split type air-conditioning systems are 310.41 MWh, 323.18 MWh and 367.01 MWh respectively. Therefore, the chiller air-conditioning system can also be considered as equally efficient as the difference between the annual energy consumption between the two systems is less than 5 %. When the annual energy consumption of these three systems are compared, split system consumes 18.2 % and 13.5 % more energy than the annual energy consumption of VRV and Chiller systems respectively.
- From the overall outcome of the simulation, it was concluded that the project team had selected the most energy efficient air-conditioning system; VRV system from the considered options; VRV, Chiller and Split systems, correctly even without performing a comprehensive analysis.

5.3 Life cycle cost analysis of the potentially applicable air-conditioning systems

According to the LCC analysis of the considered potentially applicable air-conditioning systems for the building, chiller system has the lowest OAC. The analysis reveled that OAC of Chiller, VRV and Split type air-conditioners are Rs. 9.1 Mn, Rs. 9.6 Mn and Rs. 10.1 Mn respectively. Therefore, chiller system can be considered as the most economical air-conditioning system for the building. The project team had not considered the LCC of different systems and hence not selected the most cost effective system for the building. Instead, they had selected most efficient system which was not the most economical system for the considered building.

5.4 Maintainability of the VRV air-conditioners

There had been few maintenance problems in the air-conditioning system during the initial years of operation. Leaking refrigerant through the refrigerant pipe network and weakening of the insulation of refrigerant pipes were among the major problems prevailed during this period. After the repairing of these leakages no significant fault or weakness in the air-conditioner system had been reported. The contractor has maintained the air-conditioning system satisfactorily without major interruptions or breakdowns after the rectification of problems encountered during the initial period of operation. Therefore the maintainability of the VRV air-conditioning system is satisfactory.

5.5 Conclusions and Recommendations

Considering the findings of the research study the following conclusions and recommendations were made,

- The design and project teams of the selected installation (i.e. The project team of Center for Banking Studies) have considered the following factors when selecting the appropriate air-conditioning system for the project.
  - Suitability of the proposed air-conditioning system for the building.
  - Installation convenience and space available for the installation of air-conditioning equipment, pipes, and equipments.
  - The impact of equipments installed outside the building on the external appearance and calm surrounding environment of the building.
  - Maintainability of the different systems considered for the installation.
  - Energy efficiency of the different feasible options.
- The results of computer simulation show that the Energy Efficiency of the VRV system is satisfactory. It revealed that the chiller system also performs almost efficiently as VRV system for the selected installation.
- Saving potential of VRV air conditioners could be high as 18% compared to the energy consumed by split air-conditioning systems when used for appropriate applications. This saving potential is anticipated only when system performs under partial load conditions for a considerable time period of its total operation time. Therefore, it is vital to consider the VRV system for the installations where the building occupancy is regularly varying.

- However, the project team had not performed a comprehensive LCC analysis of considered potentially applicable air-conditioning systems for the building. As a result, they had selected the most efficient system which was not the most economical system among the considered potentially applicable systems.
- It is vital to perform a comprehensive LCC in addition to the analysis of Energy Performance of considered systems as the most efficient option could not be the most economical option in certain instances. Sensitivity analysis of the LCC with respect to major components of LCC such as cost of energy and initial cost helps to justify the selection of most economical option under the prevailing trends of respective cost components.
- VRV system is more economical for the selected installation when the initial cost is less than Rs. 267,766.79 / TR under the prevailing electricity tariff. When initial cost increases further, chiller (central) system is cost effective than the VRV system. When making decisions for marginal situations, sensitivity analysis should be considered.
- There had been some maintenance problems during the initial period of operation. The major problem was the weakening of the insulation of refrigerant pipes and leaking of refrigerant through the refrigerant pipe network. After rectifying these problems several times, the system has been operated satisfactorily without major failures. Hence, there were no major concerns regarding the maintainability of the VRV air-conditioning system.
- The contractor who installed the VRV air-conditioning system had attended on the technical faults of the system satisfactorily. The capability of the technical team of the contractor on the trouble shooting and maintenance of VRV system is satisfactory.
- Maintainability of the VRV air-conditioning systems is acceptable. It is necessary to select the correct density and thickness of the refrigerant pipe insulation to minimize the possibilities of formation of condensation along the refrigerant pipes. Also, the power quality should be maintained at an acceptable level to ensure the durability and proper functionality of electronics of the VRV air conditioning equipment.

The above conclusions and recommendations has been made based on the comprehensive study performed on a single representative installation. Future studies of this nature are anticipated to make the results of this study streamlined and validated.

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