International Journal of Science and Research (IJSR)
ISSN: 2319-7064
Index Copernicus Value (2016): 79.57 | Impact Factor (2017): 7.296

Optimizing the Design & Energy Efficiency of Central Air-Conditioning Systems

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Abstract: ***To minimize the total power consumption of a central air conditioning system, optimal control variables are necessary. A simulation of a central air conditioning system and its components are modeled. Modeling of air conditioning equipment required optimization, and power consumption formulas are created from experimental data. Optimal control is applied to the central air conditioning systems. The effectiveness of optimization and accuracy of optimization calculations are verified. Prediction of air conditioning load is required for the optimization calculation. Load prediction formulas are created and the accuracy is verified. Optimization calculation is applied to general central air conditioning system. The behavior of optimization calculation results and the necessity of various trends of initial values are verified.***

1. Introduction

In a central air-conditioning system, energy-saving operations are often carried out by means of local operation control such as an air carrier system, water transfer system, etc. However, as a whole central air-conditioning system, the energy use may possibly increase. In this respect, performing optimal control operations not just locally but for the entire central air-conditioning system is important.

2. Designing of Air-Conditioning System

2.1 Basic Concepts

- ***Comfort Air-conditioning*** – a process of controlling the air temperature, relative humidity, ventilation, air movement and air cleanliness of a given space in order to provide the occupants with a comfortable indoor temperature.
- ***Air-conditioning System*** – consists of a group of components or equipment connected in series to control the environmental parameters.

2.2 Classification of Air Conditioning Systems

The purpose of classifying air conditioning systems is to distinguish one type from another and to provide a background for selecting the optimum air conditioning system based on building requirements. A classification of air conditioning systems should include the classification of air and refrigeration systems in order to define a more specific system.

Air conditioning systems can be classified into three categories corresponding to their related equipment as follows:

a) ***Individual Systems*** – use a self-contained, factory-made air conditioner to serve one or two rooms (e.g. room/ window air conditioner and split-type units).
b) ***Unitary Packaged Systems*** – similar in nature to individual systems but serve more rooms or even more than one floor, have an air system consisting of fans, coils, filters, ductwork and outlets (e.g. in small restaurants, small shops and small cold storage rooms).
c) ***Central (Hydronic) Systems*** – basically consists of three major parts:
   - Air system – air handling units (AHU), air distribution (air duct) system and terminals.
   - Water system – chilled water system, hot water system, condenser water system.
   - Central plant – refrigeration (chiller) plant, boiler plant.

An air-handling unit (AHU) is the basic piece of equipment used in an air system. It can be either a field-assembled built-up system or a factory-made unit. Because a central system always has a chilled water system, the type of coil installed in an AHU is a water cooling coil, which is different from an air handler in a packaged system, which uses a DX (direct expansion) coil.

2.3 Air and Refrigeration Systems Designation

Classification of air conditioning systems also involves classification of refrigeration system.

- An individual system uses a small, self- contained factory-assembled refrigeration system that uses a DX-coil to cool air.
- A packaged system always has a refrigeration system that uses a DX-coil to cool air directly.
- A central system has a refrigeration system that uses chilled water as a cooling medium to cool air indirectly.

In addition, in order to designate an air conditioning system more clearly and correctly, the main characteristics of its air system may be added to the description of its basic category (that is, individual, packaged, or central). More clearly specified terminology for an air conditioning system with a designated air system and primary cooling and heating plant is a combination of items from two or three of the following columns:

Table 1: Terminology for an Air-Conditioning system

Air system	Refrigeration	Air conditioning system
• Constant volume • Fan-coil • Single-zone VAV • Perimeter-heating VAV • VAV reheat • Dual-duct VAV • Fan-powered VAV	• Centrifugal • Reciprocating • Screw • Scroll • Absorption • Gas cooling • Desiccant evaporative	• Central system • Rooftop packaged system • Indoor packaged system • Split packaged system • Rooftop heat pump system • Split heat pump system • Water-loop heat pump system • Ice storage system • Chilled water storage system • Heat recovery central system

Some air systems are always central systems and some refrigeration systems are usually packaged systems. Fan - coil systems are always central systems and centrifugal or absorption refrigeration system are usually central systems. The refrigeration systems of a package system are usually a reciprocating, screw, or scroll system. A thermal storage system is always a central system.

A variable air volume (VAV) reheat screw central system, or simply VAV reheat central system, is a central air conditioning system that has a VAV reheat air system and a screw chiller plant to cool air in various AHUs. A fan-powered VAV, centrifugal, ice storage central system is a central air conditioning system that has a fan -powered VAV system for cold air distribution and an ice storage system that uses a centrifugal chiller to reduce peak electricity costs. Ice storage systems are always central systems that use brine to provide cooling.

Occasionally, an air conditioning system may exist without an air system, such as a reciprocating water-loop heat pump system, or simply water-loop heat pump system, whose water-source heat pumps may be installed in individual rooms. Note that a heat pump is always a packaged system.

If the distinctions between centrifugal, reciprocating, scroll, and screw compression are not important for an air conditioning system (for example, for a water-loop heat pump system or a single-zone VAV rooftop packaged system), just omit them. For central systems, most primary heating plants in commercial buildings use gas-fired, electric, and heat-recovery heating. Direct gas- fired and electric heaters are the most widely used. For simplicity, the designations of primary heating plants are not included in classification. In areas where the type of primary heating plant is important, gas heating, electric heating, and oil heating can be added after centrifugal, reciprocating, or screw compression, or the designation of refrigeration systems may be omitted.

2.4 The Goal of Air-Conditioning System Design

The goal of an air conditioning system design is to achieve a highly quality system that functions effectively and is energy-efficient and cost-effective. The following are essential for a system to function effectively:

- All design criteria are fulfilled, and the requirements of the owner and the user are satisfied.
- A good indoor air quality is provided.
- The system is reliable and has adequate fire protection level (e.g. smoke management).

2.5 Air Conditioning System Selection

When considering and selecting an air conditioning system, the designer must understand the building and the client's requirements and try to study and evaluate the following factors:

- Building location, surrounding environment and external climate
- Uses and functional requirements of the building
- Client's budget, investment policy and expected quality of service

The designer should consider various system options and recommend one or several that will be likely to perform as desired. Some of the selection criteria include:

- *Performance requirements* – on comfort, noise, control options, flexibility and meeting requirements of local regulations/codes
- *Capacity requirements* – range of capacity, multiple units, zoning, etc.
- *Spatial requirement* – plant room space, space for ducting and piping (vertical shafts), space for terminal equipment
- *Costs* – initial cost, operating cost and maintenance cost
- *Energy consumption* – for both economic and environment reasons
- *System qualities* – e.g. aesthetics, life, reliability and maintainability

2.6 Steps in Air Conditioning Designing:

1) Load Estimating (By Block Load/ Zone By zone)
   -Cooling
   -Heating
2) Air System Design (i.e. Central, Unitary, Chillers etc)
3) Equipment Selection (AHU's, FCU's, PACUs, etc)
4) Supporting System (Ducts works, Air terminals, diffusers etc)

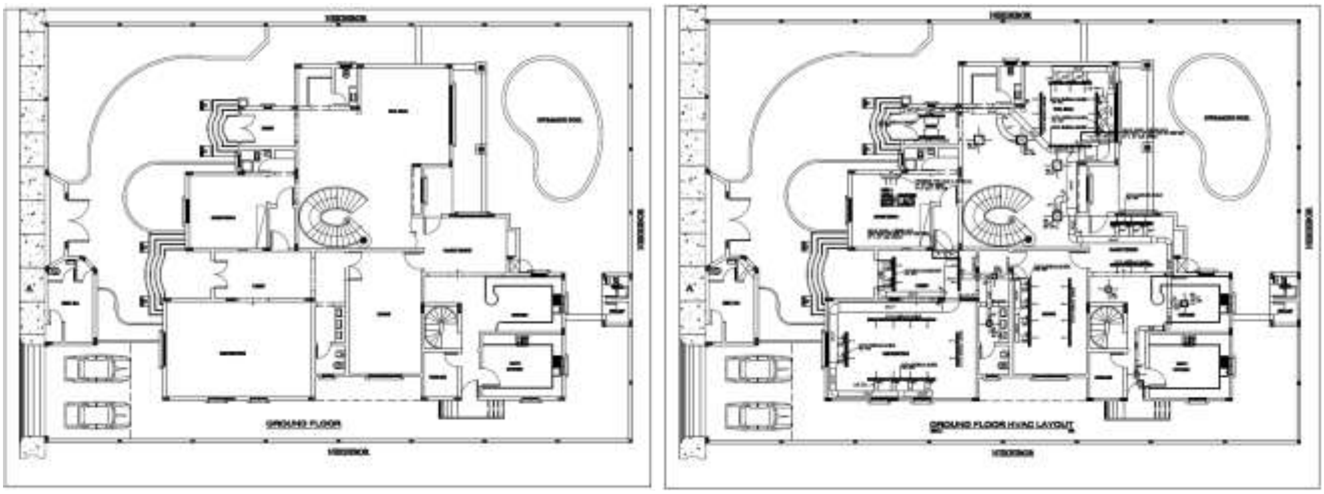

Figure 1: Ground floor (Architectural layout & HVAC designed layout)

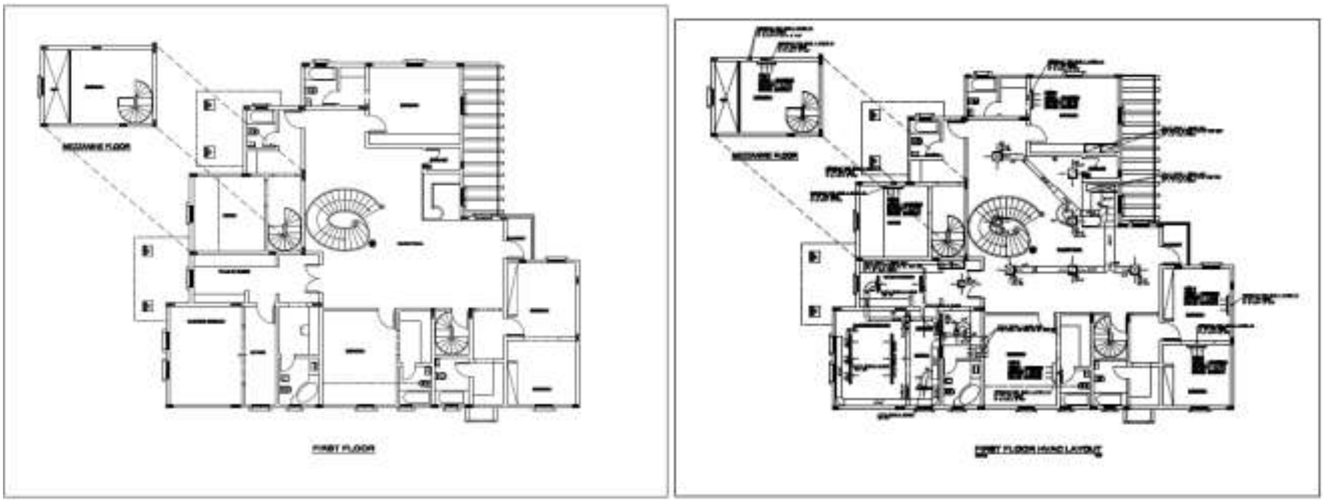

Figure 2: First floor (Architectural layout & HVAC designed layout)

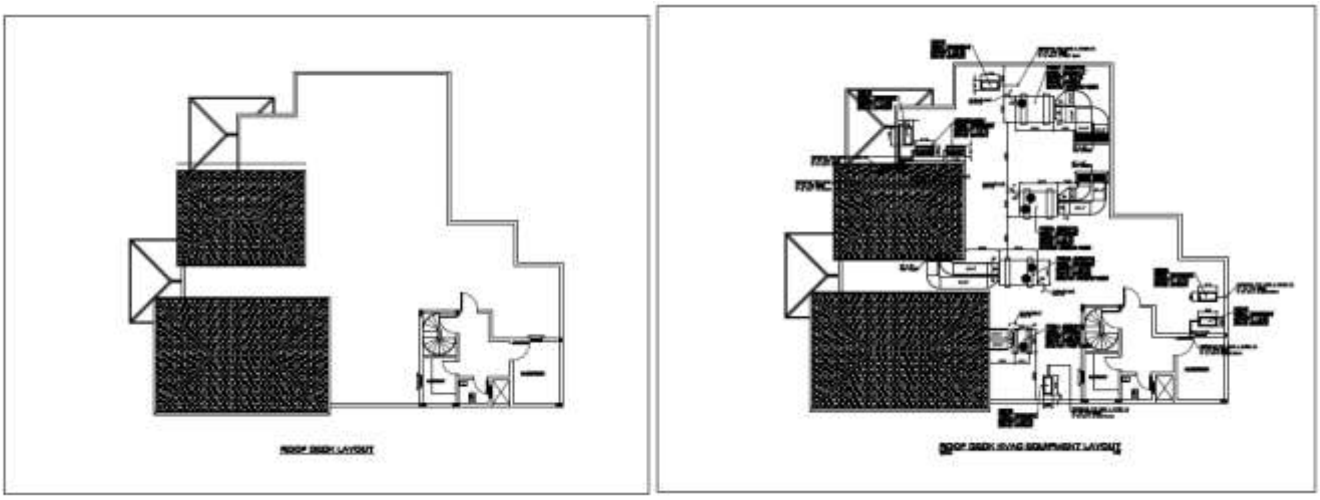

Figure 3: Roof floor (Architectural layout & HVAC designed layout)

The Energy Efficiency of Air Conditioning System

Air conditioning is widely used in Maharashtra with its hot and humid conditions. In such hot and humid climate, the energy consumed by the Heating, Ventilation and Air Conditioning (HVAC) uses up to 50%[1] of total energy consumption in a building.

Figure 1 displays the breakdown of energy consumption within a building.[1]

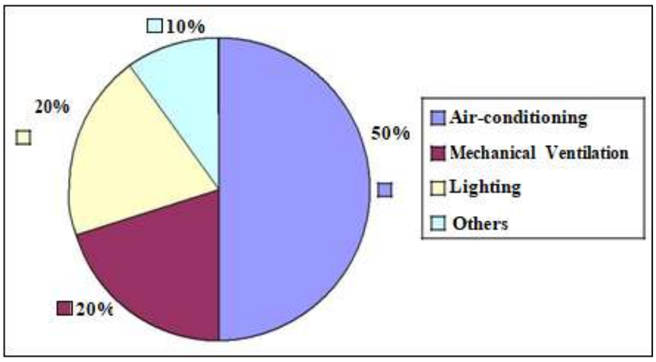

Figure 4: Breakdown of energy consumption within a building.[1]

There is potential to improve the system efficiency of the air-conditioning system. For example, the settings for air conditioners are known for their extremely low temperatures. It is a common occurrence for office staff to wear extra garments within a building.

3. Distribution of Air Conditioning Energy Consumption

The approximate distribution of the energy consumption within air conditioning is 55% for the chiller, 35% for the fans, 5% for pumps, and 5% for cooling towers. This highlights the importance of energy efficiency of the chiller in the entire cooling process. *Figure 5* displays the breakdown of air conditioning energy consumption.[2]

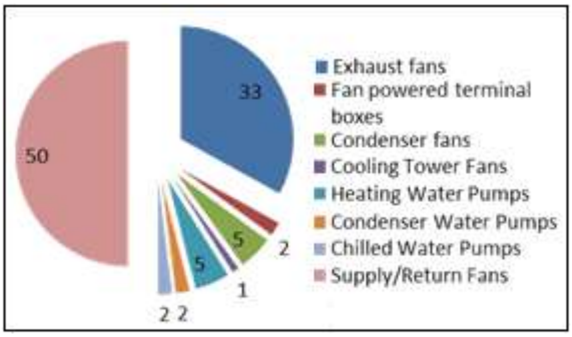

Figure 5: Breakdown of energy consumption of commercial HVAC [2]

3.1 Unitary and Central Air-Conditioning Systems

Most air-conditioning systems can be broadly classified into:

1) *Unitary systems*, which are usually simple self-contained air conditioners. These systems cover split room units, packaged units, and more advanced systems capable of varying the refrigerant flow rates (VRV);
2) *Central air-conditioning systems served by chilled water producing plants* (also known as Chillers). Central air-conditioning systems are further sub-classified into:
   a) All air systems, which circulate air treated in a central location to the conditioned space. Such systems include Constant Air Volume (CAV) systems and Variable Air Volume (VAV) systems.
   b) Air-water systems, where chilled water is circulated to fan coils and induction units located in the conditioned space.

For a cooling area of above 10,000m^2, water-cooled chillers are more efficient, rather than split-type units commonly used in households. These are typically used in commercial buildings. Due to advance in technology, the authors recommend the replacements of existing infrastructure every 10 years. The improved efficiency results in energy savings which shorten the payback time considerably to 3 years

3.2 Energy Auditing and Building Standards

All large air-conditioned public sector office buildings, as well as polytechnics and ITEs, with central air-conditioning systems and air-conditioned area greater than 10,000m^2 will be energy-audited by FY2011. Infrastructure facilities will also be energy-audited by FY2012.

Large central air-conditioning systems in buildings will be fitted with instrumentation to monitor the coefficient of performance (COP) of the air-conditioning systems. The air-conditioning systems must be upgraded to achieve a COP of at least 4.7 at the next available opportunity.

An increase of 1^{o}C in the air-conditioned indoor air temperature could reduce air-conditioning electricity consumption by about 3%. All public agencies will have to ensure that the ambient indoor air temperature of all public sector premises remain within the range of 22.5^{o}C to 25.5^{o}C.

All new office information and communication technology equipment will meet the latest Energy Star standards, where available, from FY2009 onwards.[3]

3.3 Public Sector Taking the Lead

The public sector is taking the lead by using energy and resources more efficiently. As part of this program, public sector buildings will have to meet energy efficiency targets to reduce energy expenditure.

Beyond improving building energy efficiency, all agencies are also encouraged to adopt environmentally sustainable practices that are cost beneficial, such as participating in the Water Efficient Building and Eco-Office rating frameworks developed by the Public Utilities Board (PUB) and Singapore Environment Council respectively, and implementing recycling programs.

Through this initiative, the public sector aims to demonstrate the associated environmental and economic benefits and set an example for the private sector. Public agencies are also encouraged to finance and implement their energy efficiency improvements through Performance Contracting.[3]

The Ministry of Environment and Water Resources (MEWR) and National Environmental Agency (NEA) jointly launched the Energy Efficiency Improvement Assistance Scheme (EASe) in 2005. Under this scheme, owners and operators of facilities in the manufacturing sector can obtain 50% subsidies for the engagement of energy services companies (ESCOs) to conduct energy audits on a voluntary basis. This scheme has since been extended to other commercial users and homes. In addition, for large energy consumers,[4] an energy manager has to oversee the usage of the organization to ensure energy efficiency measures are put in place. Separately, the Building Construction Authority (BCA) Green Mark Incentive Scheme for new buildings (version 4, updated in December 2010), also specified instrumentation requirements for monitoring central chilled-water plant efficiency and verification of instrumentation for the central chilled-water plant. The minimum air-conditioning system efficiencies for Green Mark Certification are given in *Figure 3*. Higher rating categories (Gold Plus and Platinum) have higher efficiency requirements (lower kW/RT).

Table 2: Minimum air-conditioning system efficiencies for Green Mark Certification

	Peak Building Cooling Load	
	< 500 RT	≥ 500 RT
	Efficiency (kW/RT)	
Water-Cooled Chilled-Water Plant	0.80	0.70
Air-Cooled Chilled-Water Plant or Unitary Air-Conditioners	0.90	0.80

3.4 An Example of Savings from Improving the Efficiency of Chiller systems

The Shangri-La Hotel in Singapore had upgraded its air-conditioning plants. It had operated an air-conditioning system of 3,252 refrigeration tonnes (RT) capacity at an average efficiency of 1.22 kW per RT. It has since upgraded the air-conditioning system with better equipment. The current installed capacity is 2,600 RT with an average system efficiency of 0.68 kW per RT. The project has resulted in a saving of 14,400 kWh of electricity per day.[5]

3.5 Efficiency and saving: Unitary systems

[o] Large consumers are mainly industrial and other commercial users whose monthly consumption exceeds 10,000 kWh.

[p] Singapore's First National Communication: Under the United Nations Framework Convention on Climate Change, 2000 (NEA).

Besides commercial buildings, the average household can also save money by investing in a more efficient air-conditioning unit. These are indicated by a higher number of energy efficiency "ticks" for the unit. A comparison of the cost savings from changing to a 4 tick unit over a 1 tick unit is given in *Figure 4*. The life-cycle cost is much lower, almost half, due to cost savings in electricity consumption. This is true for the whole range of 1 to 4 tick air-conditioners.[6] (See *Figure 5*)

Table 3: Comparison of 1 tick and 4 tick air-conditioner costs

No of ticks	1-tick	4-tick
Purchase price	$1,590	$2,180
Lifespan energy cost	$10,690	$5,470
Total life cycle cost	$12,280	$7,650

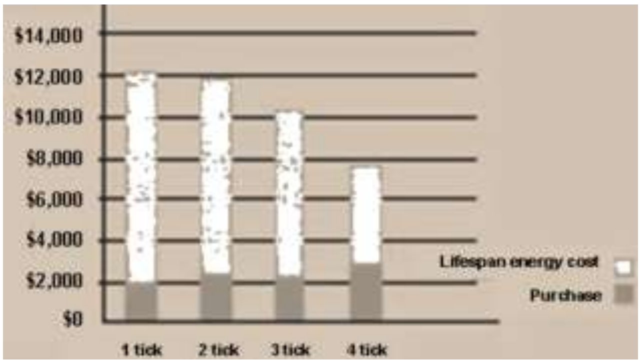

Figure 6: Comparison of capital expenditure and operating expenditure

Such split incentives in cost are most apparent in commercial settings where the capital expenditure is borne by one party and the operating expenditure is borne by another. The chiller units are often oversized by the developer to ensure that occupants do not complain that the space temperature is too high. Also, the developer does not have to bear the long-term operating cost, which is usually paid by the tenants/users of the building. Accurate sizing of chiller units for central air-conditioning would help to alleviate these problems of over-cooling in commercial buildings, and lead to sizable cost and energy savings.

3.6 Overview of HVAC System

A HVAC system in buildings may be described in general terms as a system for providing the right conditions inside the building for the thermal comfort of the occupants or the operating requirements of equipment and processes. It will usually involve the addition or removal of heat or moisture between the building interior and the exterior environment. In Singapore, because of our climatic conditions, air conditioning primarily involves cooling and dehumidification processes.

Figure 7 shows a schematic of a typical building HVAC system, divided into five heat transfer loops:[7]

1) *Indoor air loop* includes fans, cooling coils, terminal units, dampers, ducts, and controls. The air in the conditioned space is driven by fans through cooling coils and then distributed to terminal units. Dampers are used to control airflows to terminal units and fans are used to maintain a given air pressure in ducts. The cooling and ventilation loads are transferred from conditioned space to chilled water.
2) *Chilled water loop* includes pipes, pumps, cooling coils, chiller evaporators, valves, and controls. The chilled water in pipes is driven by pumps to circulate between cooling coils and chiller evaporators. Valves are used to control water flow to cooling coils. The heat is transferred from air handling units (AHUs) to chiller evaporators.
3) *Refrigerant loop* includes evaporators, compressors, condensers, expansion valves and controls. The refrigerant absorbs heat in chiller evaporators by changing phase from liquid to gas. The working of compressors makes the refrigerant a high pressure and high temperature state. The refrigerant with high temperature is cooled in chiller condensers. The high

pressure refrigerant in gas is released by expansion valves back to evaporators again with phase change. The heat is transferred from chiller evaporators to chiller condensers.

4) *Condenser water loop* includes cooling towers, chiller condensers, pumps and controls. The condenser water in chillers is delivered to cooling towers by pumps. The heat is transferred from chiller condensers to cooling towers.
5) *Outdoor air loop* includes fans, cooling towers, and controls. The outdoor air is driven by fans to go through cooling towers and to exchange heat with condenser water. The heat is transferred from cooling towers to ambient environment.

A refrigeration machine is used to maintain the evaporator coil at its low temperature by circulating a refrigerant through the coil. The refrigerant vapour at the evaporator coil is pumped to a higher pressure by a mechanical compressor where it is condensed to a liquid at another set of condenser coils. The high pressure liquid refrigerant is then allowed to expand in the evaporator coil again to complete the cycle. The heat absorbed at the evaporator coil is pumped by the refrigeration machine and rejected to the ambient at the condenser coils. Mechanical work is needed to drive the compressor. The amount of effort needed to drive the compressor is very dependent on the temperature difference at the evaporator and the condenser. The greater the difference in temperature, the greater is the effort.

This explains why ***in a simple air-conditioner, a higher thermostat set-point temperature saves energy. Similarly a reduction in the condensing temperature saves energy.***

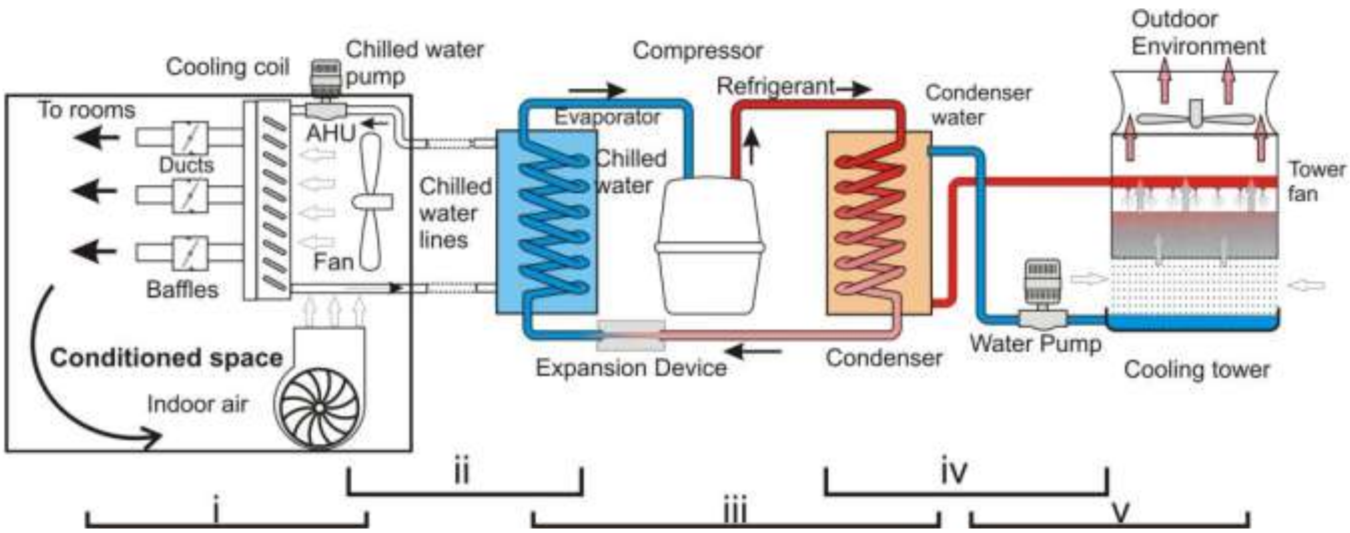

Figure 7: The schematic of a typical building HVAC system

3.7 Opportunities

(A) Use of Desiccant to Improve Energy Efficiency of Chillers

Imported air conditioners are designed to work in both summer and winter conditions. Singapore is a tropical country with an average annual ambient relative humidity of 85%. Conventional air-conditioning in hot-humid climates consists of cooling and dehumidification of the air in the conditioned space to maintain human thermal comfort. This is achieved by flowing moist air over a finned cooling coil whose surface is maintained below the moist air dew point temperature. The air gets cooled and dehumidified.

- The energy removed from the air is considered the sensible load.
- The energy in the moisture removed forms the latent load.

Since energy consumed by the chiller depends very much upon the surface temperature of the cooling coil, the energy consumed by the chiller would be reduced significantly by raising this surface temperature. Thus, if the removal of moisture in the air[8] can be handled by other means apart from condensation, e.g. by the use of desiccant, the cooling energy[9] can be reduced. Other forms of energy are still required to regenerate the desiccant (waste heat from industrial processes, solar thermal, *etc.*), but there can still be an overall reduction in energy consumed by this process of separately cooling by refrigeration and dehumidification by desiccant.

(B) Improvements Needed to Existing Control Systems

The adoption of advanced reliable and cost effective control systems aims to optimize the running of the HVAC system. The current Building Automation Systems (BAS) and Energy Management Systems (EMS) do provide certain procedures to improve energy efficiencies and human comfort for building HVAC processes. However, ***the authors assess that the very large amount of data involved places huge burdens on the communication network and the processing capacities of the systems. In order to relieve these burdens, they treat many variables as constants and each of these function loops operates independently***. This kind of operation will require more energy than actually required for the circulation of refrigerant, air, or water to maintain the specified indoor environment. Wireless technology as well as improved communications protocols efficient sensor nodes and sensor network platform should be developed. With the deployed sensor nodes, information regarding various outdoor and indoor environmental conditions can be obtained.

(C) Importance of Air Ducts

The air duct is the major component transmitting the conditioned air to the space. ***The authors assess that excessive energy use by the distribution fans in the HVAC can be minimized through the optimizing of ducts, bends, fittings and accessories. In particular, the routing of ducts within conditioned spaces will also minimize cooling losses and any leakage effects.***

4. Optimization

4.1 Optimization Calculation Method

Using a simulation program, a control variable to minimize power consumption is obtained by a sequential quadratic programming method in the non-linear programming with restriction. An optimal solution is attempted in order to find the constrained minimum of a scalar function of several variables starting at an initial estimate. The optimized calculation program can be divided into four modules: a program using a sequential quadratic programming method to perform the optimization calculation, a program to indicate the constraints (restrictive conditions) in the optimization calculation, a program to solve the performance function (electric power calculation formula), and a simulation

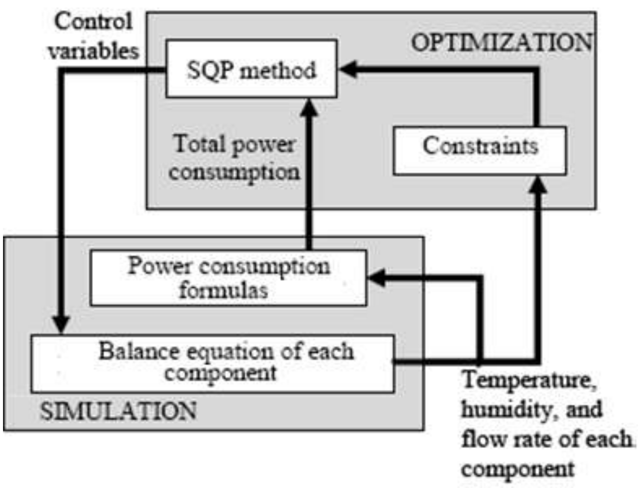

Figure 8: The Flow of Optimization

The Energy saving tips:-

1) **Use an AC timer or smart thermostat:**
   For **central AC**, your thermostat might already have a timer built-in. If not, you can replace your thermostat with a programmable one.
   For **window unit AC's**, many modern units have a timer built in. If not, you can use a simple plug-in timer if your AC has a mechanical on/off switch (i.e., you physically move it into a different position when you turn the AC on).
2) **Close registers in unused rooms :** If you have central AC you can close registers in rooms you're not using so you're not paying to cool them, but note that if you close too many of them, the pressure in the system could cause leaks in the ducts. Check with an AC professional first to see how many & which registers are safe to close at the same time.
3) **Clean the filter:** Clean or replace your AC filters every month. A dirty filter makes your AC work harder, which uses more electricity.
4) **Don't oversize when buying a new AC:** An AC that's too big is inefficient and wastes money! You want your AC to run at least ten minutes when it kicks in. Oversized AC's cool the house down too quickly and then cut off before they've reached their most efficient running level. A properly-sized system that runs longer saves money over an oversized system that runs for shorter periods of time.
5) **Cool your condenser or window unit:** An AC Mister makes your AC run more efficiently by cooling the condenser with water vapor as it runs.
6) **Shade your condenser or window unit:** Condensers in the shade use up to 10% less electricity than those in direct sunlight.
7) **Don't block the condenser unit:** Tall grass and other debris on or around the condenser can restrict air flow and use more electricity.
8) **Clean the condenser/evaporator coils at the beginning of each season:** You can wash the fin coils on the outside with a garden hose. Unless you know what you're doing, have the coils on the inside serviced by an AC specialist
9) **Test your ducts for leaks:** Austin Energy tested thousands of home duct systems and found that **the average home loses 27% of its heating or cooling from leaky ducts**. (June 2006) And**over 86% of homes had ducts which lost more than 10%.** (June 2009) Leaking ducts and insufficient insulation meant that the average home used 162 kWh/mo. extra electricity per month (July 2009), or 18% more than normal. This is an extra **$233 a year** at average electrical rates.
10) **Make sure your doors and windows are well sealed:** You'll pay a lot more to cool your home when the cold air easily escapes. Do-it-yourself weather stripping for doors and caulk for windows is easy to install, and cheap. Also make sure to caulk around the holes where pipes go into the wall under sinks.

5. Conclusion

This paper describes the Optimization of Design and Energy efficiency of Central air-conditioning system.

The optimization model for the overall energy-saving control of the central air-conditioning system has been studied based on the mathematical calculations.

The optimization model has been used to study a central air-conditioning system. The hourly optimal conditions of all equipments in this system on one operation day were obtained by the optimization model using the decomposition–coordination method, and the potential energy saving was analyzed.

The results of SCOP (System coefficient of performance) under optimal operation and non-optimal operation manifest that the energy saving brought by the optimization scheme will become more significant under the lower load operation of the air-conditioning system.

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