

**STUDY, MODELING, ANALYSIS, EVALUATION,  
SELECTION AND PERFORMANCE IMPROVEMENT OF  
AIR CONDITIONING SYSTEM**

A thesis submitted in the partial fulfillment of the  
requirements for the award of degree of

**Master of Engineering**

**in**

**Thermal Engineering**

Submitted By

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**JULY 2012**

## ACKNOWLEDGEMENT

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Words are often less to reveal one's deep regards. With an understanding that work like this can never be the outcome of a single person, I take this opportunity to express my profound sense of gratitude and respect to all those who directly or indirectly helped me through the duration of this work.

I take the opportunity to express my heartfelt adulation and gratitude to my supervisor, **Dr. V.P. AGRAWAL** for their unreserved guidance, constructive suggestions, thought provoking discussions and unabashed inspiration in the nurturing work. It has been a benediction for me to spend many opportune moments under the guidance of the perfectionist at the acme of professionalism. The present work is testimony to their activity, inspiration and ardent personal interest, taken by them during the course of this work in its present form. I am grateful to **Dr. Ajay Batish**, Prof. & Head, MED for providing the facilities for the completion of the work.

The non teaching staff Mr. Charanjit Singh, Mr. Jaswinder Singh, Mr. Pankaj Kumar deserves special thanks for their help during the period of this work. No words acknowledge the support I received from my friends for their valorous help and co-operation.

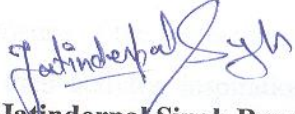
I take pride of myself being son of ideal parents for their everlasting desire, sacrifice, affectionate blessings, and help, without which it would not have been possible for me to complete my studies.

I would like to thank to all the members and employees of Mechanical Engineering Department, Thapar University Patiala for their everlasting support. Above all, I express my indebtedness to the "ALMIGHTY" for all His blessing and kindness.


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## DECLARATION


I hereby declare that the thesis entitled “**STUDY, MODELING, ANALYSIS, EVALUATION, SELECTION AND PERFORMANCE IMPROVEMENT OF AIR CONDITIONING SYSTEM**” is an authentic record of my study carried out as requirement for the award of degree of **Master of Engineering (Thermal Engineering)** at **Thapar University, Patiala** under the guidance of **Dr. V.P. AGRAWAL**, visiting Professor, Department of Mechanical Engineering, Thapar University, Patiala during **July 2011 to July 2012**. The matter embodied in this report has not been submitted in part or full to any other university or institute for the award of any other degree.


  
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This is to certify that above declaration made by the student concerned is correct to the best of my knowledge and belief.

  
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## ABSTRACT

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Air conditioning is a broader aspect which looks into the simultaneous control of all mechanical parameters which are essential for the comfort of human beings or animals or for the proper performance of some industrial or scientific process. Air conditioning system is a device consisting of components and equipment arranged in sequential order to satisfy the various space conditions required for comfort as well as industrial air conditioning. Various types of air conditioning applications are: apartment buildings, banks, office buildings, hospitals, industrial plants, schools, restaurants, department stores, hotels, etc. Increased demands for air conditioning have brought about rapid increase in number of air conditioning systems and air conditioner manufacturers. This growing demand for air conditioning systems which provide appropriate performance on the whole life basis has brought about many changes in the attention focused on the proper selection of air conditioning system.

In this thesis work, a new methodology has been developed for the evaluation, comparison, ranking and optimum selection of an air conditioning system from the different alternative designs available in the global market. This proposed methodology is based on Multi Attribute Decision Making (MADM) approach. Pertinent attributes which describe the whole air conditioning system are identified in an exhaustive way. A n-digit coding scheme based on all the pertinent attributes for a given air conditioning system is suggested, that is useful for the development of a comprehensive database of available air conditioning systems, and their subsequent retrieval. The air conditioning system selection procedure allows rapid convergence from a very large number of options to a manageable shortlist of potentially suitable air conditioning systems using 'Elimination Search' based on few critical selection attributes. Then the selection procedure proceeds to evaluate and rank the shortlisted alternatives by employing the TOPSIS approach. Three graphical techniques of comprehensive comparison namely histogram, graphical and radar are also presented to better educate the decision makers. The proposed 3-stage selection methodology is explained with the help of an illustrative example. This methodology provides good insight to the air conditioning system manufacturer so that he can improve his product or introduce new product to fulfill the need of customer. It will also help the designer at various design stages, while the maintenance people can plan maintenance strategy to reduce the down time.

An integrated systems model for the structure of the air conditioning system in terms of its constituents and interactions between the constituents is developed using graph theoretic approach. The different constituents and the interaction between the constituents are identified and have been represented by graph-based model. The information of the graph is converted into matrix form. The matrix models and the variable permanent function models are developed for carrying out decomposition, characterization, and the total analysis. The terms of permanent multinomial characterize the air conditioning system uniquely and are highly useful for computational storage, retrieval, communication, as well as analysis of the structural information of air conditioning system. To illustrate the effectiveness of the Graph Theoretical Approach, the case study of an existing central air-conditioning system in a library building (located at Thapar University, Patiala City) is also presented.

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# CHAPTER 1

## INTRODUCTION

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### 1.1 Introduction to Air Conditioning

With the development of society and economy, living standard of people is improving, and higher living conditions are demanded. So, more attention is paid towards treating the indoor air for the comfort of the occupants. Apart from comfort air conditioning required for comfort of persons, air conditioning is also used to provide conditions that some industrial processes require. Merely lowering or raising the temperature does not provide comfort in general to the machines or its components and living beings in particular. In case of the machine components, along with temperature, humidity also has to be controlled and for the comfort of human beings along with these two important parameters, air motion and cleanliness also play a vital role. Air conditioning, therefore, is a broader aspect which looks into the simultaneous control of all mechanical parameters which are essential for the comfort of human beings or animals or for the proper performance of some industrial or scientific process. The precise meaning of air conditioning can be given as the process of treating air in an internal environment to establish and maintain required standards of temperature, humidity, air movement and air cleanliness for the health and comfort of the occupants, for product processing, or both. In some applications, even the control of air pressure falls under the purview of air conditioning.

Depending upon the requirement, air conditioning is divided into the summer air conditioning and the winter air conditioning. In the summer air conditioning, apart from cooling the space, in most of the cases, extra moisture from the space is removed, whereas in the winter air conditioning, space is heated and since in the cold places, normally the humidity remains low, moisture is added to the space to be conditioned. The summer air conditioning thus uses a refrigeration system and a dehumidifier. The winter air conditioning uses a heat pump (refrigeration system operated in the reverse direction) and a humidifier. Depending upon the comfort of the human beings and the control of environment for the industrial products and processes, air conditioning can also be classified as comfort air conditioning and industrial air conditioning. Comfort air conditioning deals with the air conditioning of residential buildings, offices spaces, cars, buses, trains, airplanes, etc. Industrial air conditioning

includes air conditioning of the printing plants, textile plants, photographic products, computer rooms, etc.

## **1.2 The Need for Air Conditioning**

Although some people might regard air conditioning as a luxury, in certain areas having air conditioning is a must. One does not feel comfortable if the temperature and humidity level is too high. Air conditioning affects not only personal comfort, but also economics. If people feel comfortable, their productivity is generally better than if they work under uncomfortable conditions. Apart from comfort air conditioning required for comfort of persons, air conditioning is required in many industries to provide conditions that some processes require. The life and efficiency of electronic devices increases at lower temperatures. Computer and microprocessor-based equipment also require air conditioning for efficient operation. Thus, air conditioning is and will be more and more needed in our world.

## **1.3 History of Air Conditioning**

For prehistoric people, open fires were the primary means of warming their dwellings; shade and cool water were probably their only relief from heat. No significant improvements in humankind's condition were made for millions of years. The fire-places in the castles of medieval Europe were hardly an improvement. They only heated the area immediately around them. Paintings from those times show that the kings and queens wore furs and gloves indoors in winter.

There were a few exceptions to this lack of progress. The ancient Romans had remarkably good radiant heating in some buildings, which were achieved by warming air and then circulating it in hollow floors or walls. In the dry climate of Middle East, people hung wet mats in front of open doorways and achieved a crude form evaporative air cooling. In Europe, Leonardo da Vinci designed a large evaporative cooler.

The development of effective heating ventilation, and air conditioning, however, was begun scarcely 100 years ago. Central heating systems were developed in the nineteenth century, and summer air conditioning using mechanical refrigeration has grown into major industries only in last 60 years [1]. The first air conditioning system was used for industrial as well as comfort air conditioning. Eastman Kodak installed the first air conditioning system in 1891 in Rochester, New York for the storage of photographic films. An air conditioning system was installed in a printing press in 1902 and in a telephone exchange in Hamburg in 1904. Many

systems were installed in tobacco and textile factories around 1900. The first domestic air conditioning system was installed in a house in Frankfurt in 1894. A private library in St Louis, USA was conditioned in 1895, and a casino was air conditioned in Monte Carlo in 1901. Efforts have also been made to air condition passenger rail coaches using ice. The widespread development of air conditioning is attributed to the American scientist and industrialist Willis Carrier. Carrier studied the control of humidity in 1902 and designed a central air conditioning plant using air washer in 1904. Due to the pioneering efforts of carrier and also due to simultaneous development of different components and controls, air conditioning quickly became very popular, especially after 1923 [2]. At present air conditioning is widely used in residences, offices, commercial buildings, hospitals and in mobile applications such as rail coaches, automobiles, aircrafts etc. Industrial air conditioning is largely responsible for the growth of modern electronic, pharmaceutical, chemical industries etc.

#### **1.4 Air Conditioning System**

A system consisting of components and equipment arranged in sequential order to satisfy the various space conditions required for comfort as well as industrial air conditioning is known as air conditioning system. In order to provide complete air conditioning, a year-round system must have following functions: heating, cooling, dehumidification, humidification, ventilation, filtration, and air circulation. The size and complexity of the air conditioning system may range from a single space heater or window unit for a small room to huge system for building complex, yet the basic principles are same.

#### **1.5 Working Principle of Air Conditioning System**

There are many methods to implement air conditioning, such as the vapour compression refrigeration process and the absorption refrigeration system. The most common method in practice is the vapour compression refrigeration process. Simple vapour compression refrigeration cycle consists of four main components, which are cooling coil or evaporator, compressor, condenser and an expansion valve as shown in figure 1.1

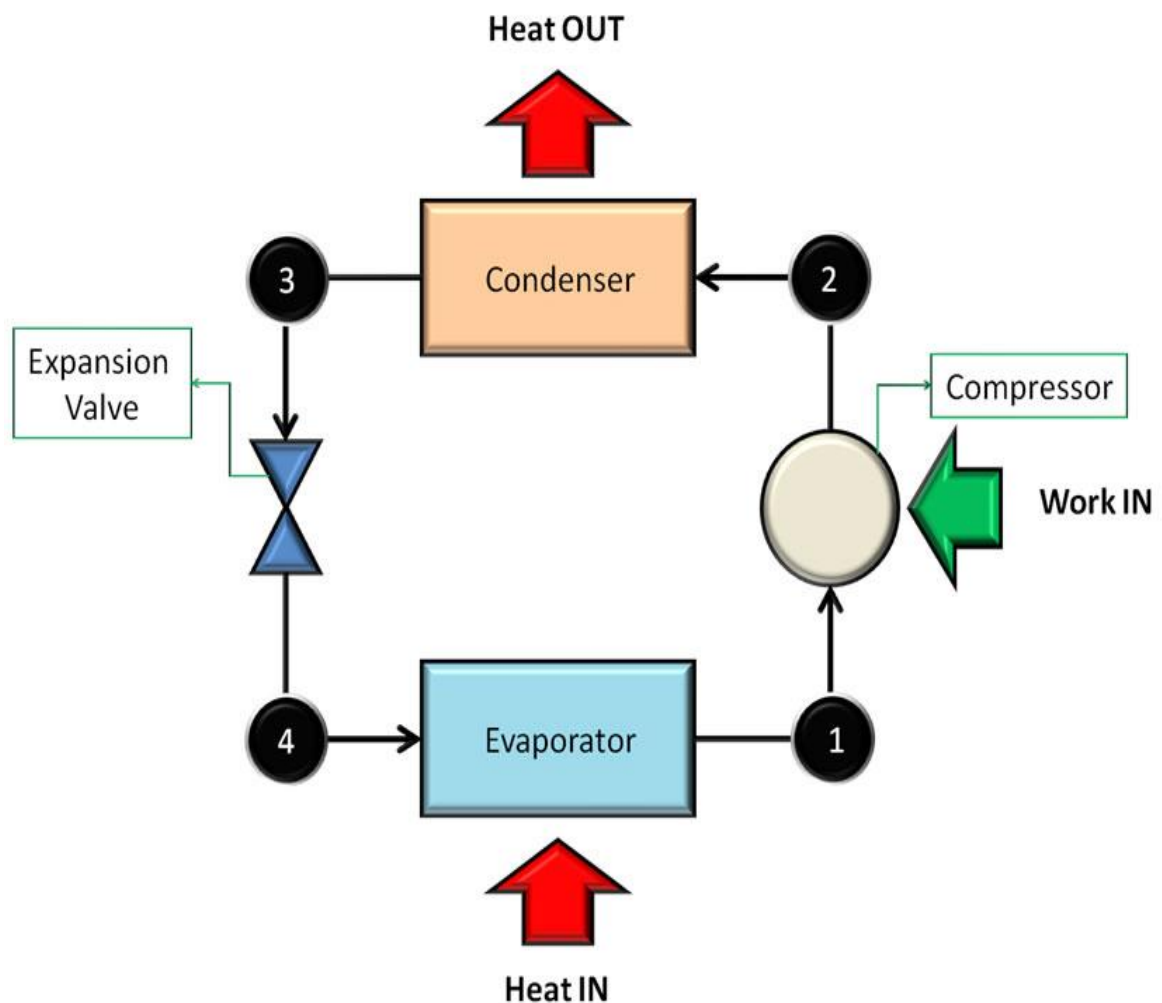


Figure 1.1 Schematic of a Vapour Compression Refrigeration Cycle

In this process, warm air is forced to pass through an evaporator coil where air is cooled by a low-temperature two-phase refrigerant in the coil. If the evaporator surface temperature is lower than the air dew-point temperature, the air is dehumidified by the coil. The heat, which is transferred from warm air, changes the refrigerant from liquid to vapour. The compressor removes the low temperature and low pressure refrigerant vapour from the evaporator coil and discharges that vapour at a high temperature and high pressure to a condenser. In the condenser, the heat of the refrigerant is removed by a coolant, which often is water or air, causing the refrigerant to return to a liquid state at that high pressure. The high pressure liquid refrigerant passes through a throttling device and becomes a low pressure and low temperature two-phase, vapour plus liquid, state refrigerant. The refrigerant then passes into

the evaporator to cool and to dehumidify warm air. After heat and mass are transferred, the lower temperature and lower humidity air is sent to the air conditioned space to balance heat and humidity load of air conditioned space. It should be observed that the system operates on a closed cycle. The system requires input in the form of mechanical work. It extracts heat from a cold space and rejects heat to a high temperature heat sink. This refrigeration system can also be used as a heat pump, in which the useful output is the high temperature heat rejected at the condenser. Alternatively, a refrigeration system can be used for providing cooling in summer and heating in winter.

Based on figure 1.1, ideal vapour compression refrigeration cycle consists of four processes:

- 1-2 Isentropic compression in compressor
- 2-3 Constant-pressure heat rejection in a condenser
- 3-4 Throttling in an expansion device
- 4-1 Constant-pressure heat absorption in an evaporator

Figure 1.2 shows the T-s diagram for the ideal vapour compression refrigeration cycle. The refrigerant enters the compressor at state 1 as saturated vapour and is compressed isentropically to the condenser pressure. During the isentropic compression process the temperature of the refrigerant increase to well above the temperature of the surrounding medium.

The refrigerant then enters the condenser as superheated vapour at state 2 and leaves as saturated liquid at state 3, as result of heat rejection to the surrounding. The temperature of the refrigerant at this state is still above the temperature of the surroundings.

The saturated liquid refrigerant at state 3 is throttled to the evaporator pressure by passing it through an expansion valve. During this process the temperature of the refrigerant drops below the temperature of the refrigerated space. The refrigerant enters the evaporator at state 4 as a low-quality saturated mixture, and it completely evaporates by absorbing heat from refrigerated space. The refrigerant leaves the evaporator as saturated vapour and reenters the compressor, completing the cycle.

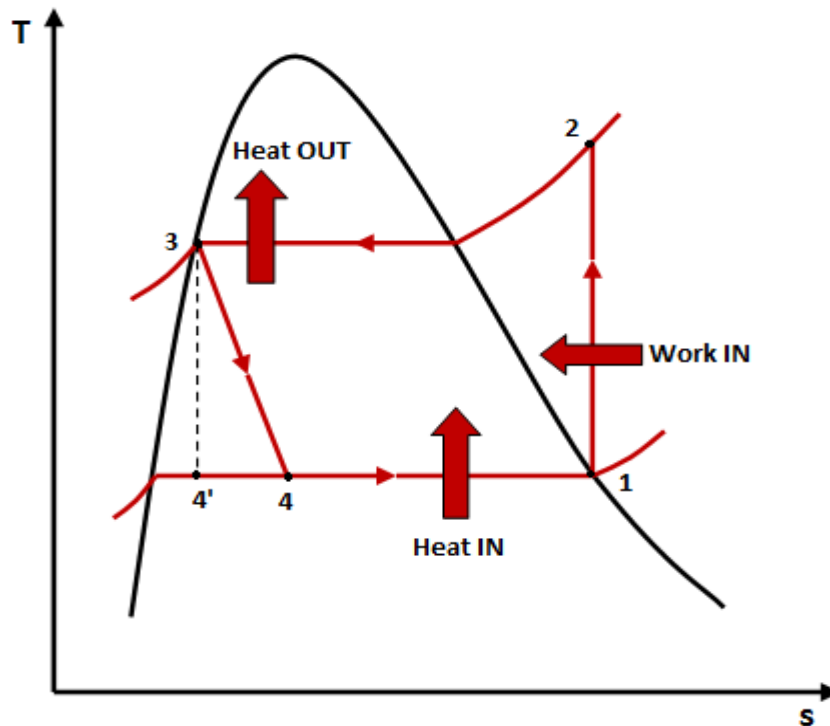


Figure 1.2 T-s Diagram for the Ideal Vapour Compression Refrigeration Cycle

### 1.6 Types of Air Conditioning Systems

In institutional, commercial, and residential buildings, air-conditioning systems are mainly for the occupants' health and comfort. They are often called comfort air-conditioning systems. In manufacturing buildings, air-conditioning systems are provided for product processing, or for the health and comfort of workers as well as processing, and are called processing air-conditioning systems.

Based on their size, construction, and operating characteristics, there are several choices for the type of air conditioning systems, each satisfying the air conditioning system objectives with different degrees of success. Broadly the air conditioning system can be classified in two broad categories: 1) Decentralized systems and 2) Centralized air conditioning systems.

Decentralized air conditioning systems typically serve single or small spaces from a location within or directly adjacent to the space. These are essentially direct expansion (DX) type, where the air is cooled directly exchanging heat from the refrigerant. These systems are widely used in small to medium sized buildings. For larger and more complex applications,

centralized air conditioning systems are used. These systems serve multiple spaces from one base location. These typically use chilled water as a cooling medium and use extensive ductwork for air distribution.

The principle advantages of **decentralized** air conditioning systems is lower initial costs, simplified installation, no ductwork or pipes, independent zone control, and less floor space requirements for mechanical room, ducts and pipes. A great benefit of decentralized systems is that they can be individually metered at the unit. Disadvantages are short equipment life (10 years), higher noise, higher energy consumption (kW/ton) and are not fit where precise environmental conditions need to be maintained.

The principal advantages of **central** air conditioning systems are better control of comfort conditions, higher energy efficiency and greater load-management potential. The main drawback is that these systems are more expensive to install and are usually more sophisticated to operate and maintain.

### 1.6.1 Decentralized Systems

Decentralized air conditioning systems commonly known as by various generic names viz. local systems, individual systems, floor-by-floor systems, unitary systems or packaged systems provide cooling to single room/spaces rather than the building. These are also referred to as “Direct Expansion” or DX types since the cooling is delivered by exchanging heat directly with a refrigerant type cooling coil and these do not use chilled water as an intermediate cooling medium. Figure 1.3 shows the schematic of typical DX air conditioning system.

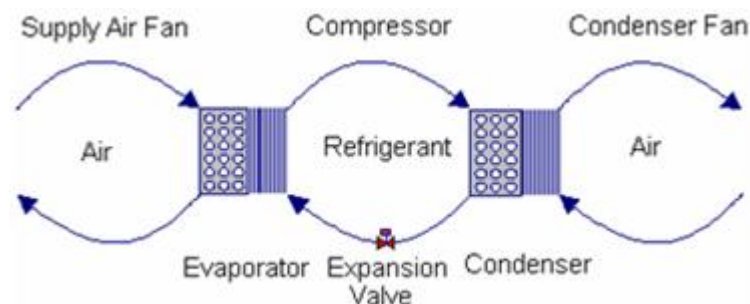


Figure 1.3 [3] DX System

In this schematic, the heat is extracted from the space and expelled to the outdoors (left to right) through 3 loops of heat transfer.

- In the leftmost loop, a supply air fan drives the indoor air across the evaporator, where it transfers its heat to the liquid refrigerant. The resultant cooled air is thrown back to the indoor space. The liquid refrigerant is vaporized in the tubes of the evaporator.
- In the middle loop, a refrigeration compressor drives the vapour refrigerant from evaporator to the condenser and back to the evaporator as a liquid refrigerant. The cycle continues in closed loop copper tubing.
- In the rightmost loop, a condenser air fan drives the ambient air across the condenser, where it transfers heat of refrigerant to the outdoors. The refrigerant is cooled and liquefied after expanding it through an expansion valve located between condenser and the evaporator.

These units are factory assembled; self-contained units commonly sold as "off the shelf," package units of varying capacity and types. Each package consists of refrigeration and/or heating units with fans, filters and controls. Depending upon the requirement these are in the form of room air conditioners, split air conditioners, heat pumps and packaged air conditioner with air cooled or water cooled condensing options

For large buildings decentralized systems may be viewed as collection of multiple independent units placed at different locations in a distributed network with each unit working in isolation. Each system is local self-contained unit consisting of its own compressor/s, evaporator coil, fan, condensing unit and filtration unit. Depending upon the capacities required and areas served the decentralized equipment category includes:

- Window air conditioners;
- Residential and light commercial split systems;
- Packaged thru-the-wall and window air conditioners;
- Self-contained (floor by floor) package systems;
- Commercial outdoor roof top packaged systems
- Heat pumps

Since in DX systems, the air is cooled directly by the refrigerant the cooling efficiency is higher. However, it is not always feasible to carry the refrigerant piping to the large distances,

therefore the DX type system is usually used for cooling the small buildings or the rooms on the single floor. For this reason, decentralized systems are essentially floor by floor standalone, self contained units each working independent of each other.

### 1.6.1.1 Window Air Conditioner

Window air conditioner provides cooling only when and where needed and is less expensive to operate. 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 which is fitted in a slot in the wall of the room, or often a window sill. Room air conditioners are generally available in capacities varying from about 0.5 TR to 3 TR.

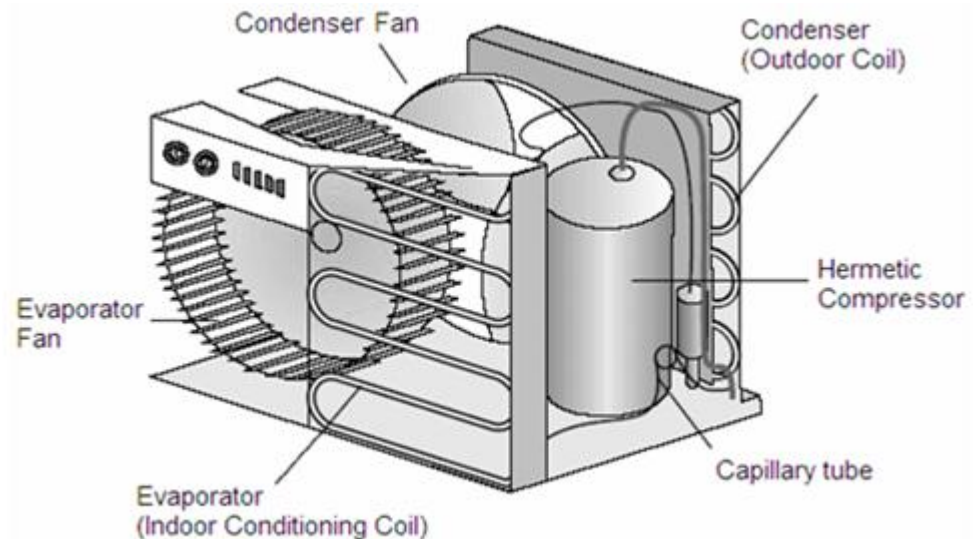


Figure 1.4 [4] Typical Room Air-Conditioner

### 1.6.1.2 Split Air Conditioning Systems

The split air conditioner 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. The indoor and outdoor units are connected by refrigerant piping. Split-systems are popular in small, single-story buildings. Flexibility is the overriding advantage of a split system. Because a split system is connected through a custom designed refrigerant piping system, the engineer has a large variety of possible solutions available to meet architectural

and physical requirements particularly for buildings with indoor and/or outdoor space constraints.

In both window mounted and split type air conditioners, the cooling capacity is controlled by switching the compressor on-and-off. Sometimes, in addition to the on-and-off, the fan speed can also be regulated to have a modular control of capacity. It is also possible to switch off the refrigeration system completely and run only the blower for air circulation. Both the split type air conditioner and room air conditioners are equally reliable but it is not possible to provide fresh air in split air conditioners. Room air conditioners generally have small damper for letting the fresh air in.

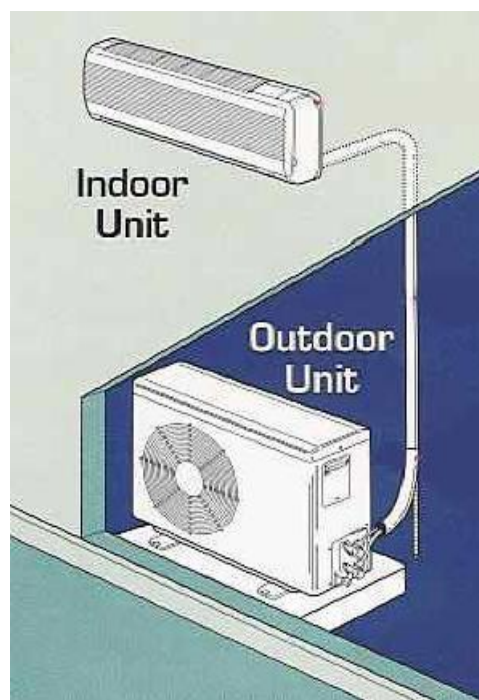


Figure 1.5 Split air conditioning system

### **1.6.1.3 Variable Refrigerant Flow (VRF) Split System**

A VRF air-conditioning system is essentially a sophisticated split system with an added ability to provide cooling on an individual basis to multiple rooms from a common condenser. Central to VRF control is their ability to automatically vary refrigerant flow in response to the heating/cooling load of the building. Occupant control is very simple, with easy to use wall-mounted key pads or hand held remote controllers providing individual control of room units. This is particularly useful in applications such as office blocks, hotels and large retail stores etc. which may need cooling in some areas and heating in other areas.

VRF systems are complex and contain microprocessor-based electronics, which ensure efficient operation and simple individualized control.

#### 1.6.1.4 Packaged Air Conditioners

Packaged air conditioning systems consist of pre-assembled, off-the-shelf equipment that provides space heating, cooling, and ventilation to small and medium spaces. These systems are available in capacities ranging from about 5 TR to up to about 100 TR. Small capacity Individual room air conditioning systems are essentially ductless while larger package units use ductwork for air distribution. Obviously the larger the tonnage, the larger will be the airflow and it will require ductwork to cover all spaces and to reduce noise. It is also possible to house the entire refrigeration in a single package and may also include heating coils along with the evaporator. The condenser used in these systems could be either air cooled or water cooled. Figure 1.6 shows a packaged air-conditioning water cooled unit designed to operate with dual compressors.

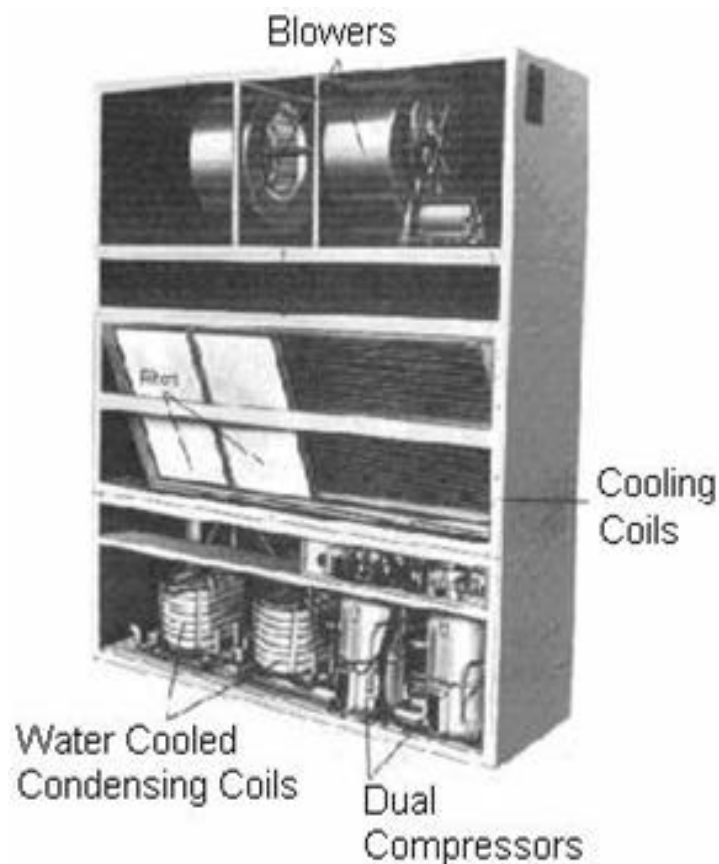


Figure 1.6 Packaged Air-Conditioner Units

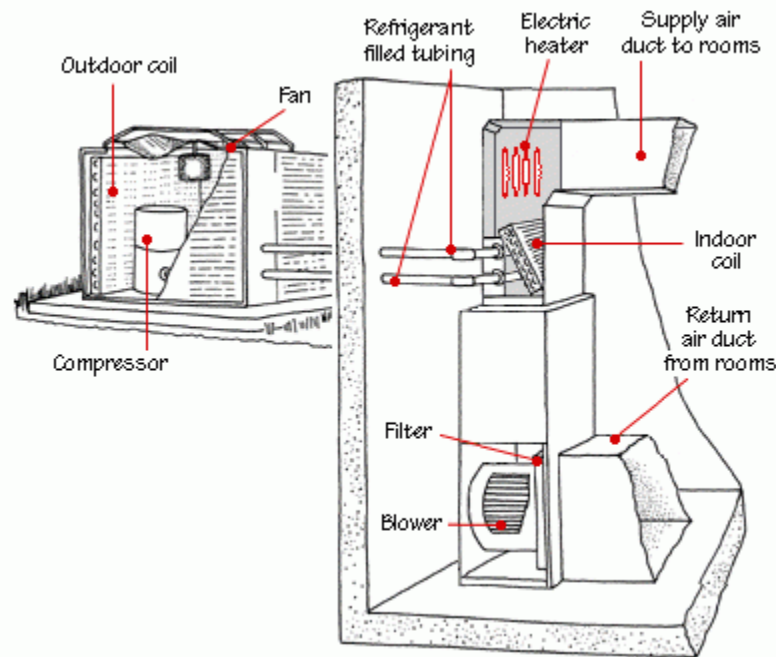


Figure 1.7 [4] Package Type Split System

### 1.6.1.5 Package Terminal Air Conditioners (PTAC)

Package terminal air conditioners (PTAC) also called "through-the-wall" air conditioners are relatively small systems typically below 7.5 TR and require no external ductwork. They are like a commercial quality version of residential window-mounted air conditioners (although they are actually mounted at floor level in a sleeve passing through the building wall). Ductless products are fundamentally different from ducted systems in that heat is transferred to or from the space directly by circulating refrigerant to evaporators located near or within the conditioned space. In contrast, ducted systems transfer heat from the space to the refrigerant by circulating air in ducted systems.

### 1.6.1.6 Single Package Rooftop Systems

These systems consist of a single rooftop-mounted unit that contains all mechanical elements of the air conditioning system, including compressors, condensers, and evaporators. The units also include a supply fan and filter system that connects to the ductwork to provide air to the conditioned space or can be used with air distribution ductwork. The typical capacity for a rooftop-packaged unit is 5 to 130 tons. Rooftop units work well for single-story buildings, but don't fit into multi-story schemes. These units are popular for general air-conditioning of

stores, residences, schools, offices, etc. particularly suitable for single flat building with extensive floor areas.

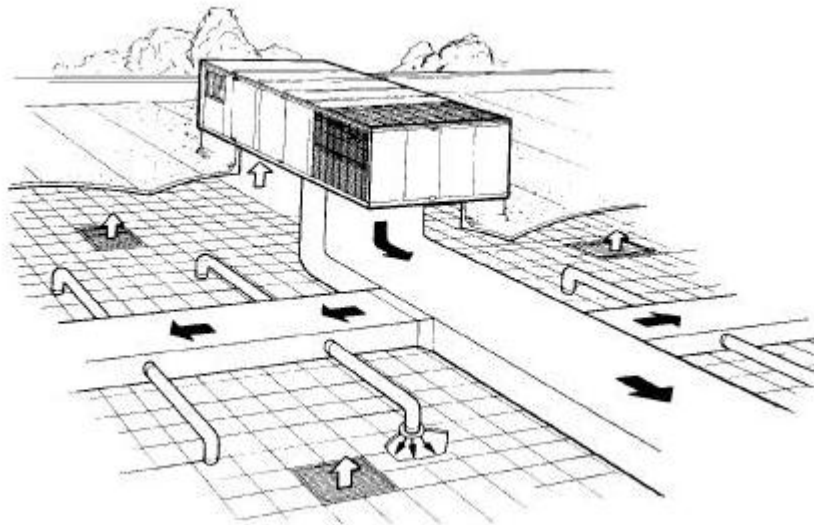


Figure 1.8 Typical rooftop installation of the single-zone system

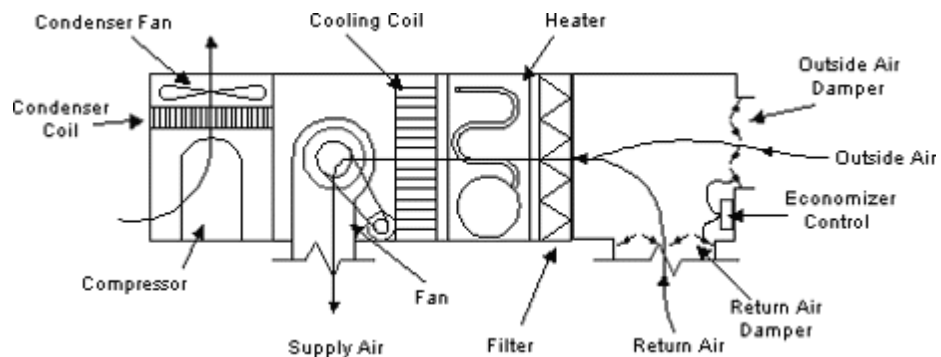


Figure 1.9 [4] Typical Single-Package Rooftop System

### 1.6.1.7 Heat Pumps

DX systems operating in reverse cycle are called “Heat pumps”. Through an addition of a special 4-way reversing valve, heat flow in mechanical refrigeration loop can be reversed so that heat is extracted from outside air and rejected into the building. Heat pumps provide both heating and cooling from the same unit and due to added heat of compression, the efficiency of heat pump in heating mode is higher compared to the cooling cycle. In the summer heat pumps work like a standard air conditioner removing heat from inside your home and transferring it to the outside through the condenser coil. In the winter heat pumps run in

reverse removing heat from the outdoor air and transferring into the home by the evaporator coil, which now becomes a condenser coil in the heating mode. As the temperature drops outside, the unit must work harder to remove heat from the air, lowering its efficiency. At this point, a heat pump system will use supplemental electric resistive heaters to warm the air to the proper temperature.

### 1.6.1.8 Heat Rejection

Most decentralized systems use air-cooled finned tube condensers to expel heat. The larger packaged air conditioners may be water cooled or air cooled. The water cooled systems use shell and tube type condenser.

### 1.6.2 Central Systems

Centralized systems are defined as those in which the cooling (chilled water) is generated in a chiller at one base location and distributed to air-handling units or fan-coil units located throughout the building spaces. The air is cooled with secondary media (chilled water) and is transferred through air distribution ducts. These are usually pre-packaged by the manufacturer with the evaporator and condenser attached, so that only water pipes and controls must be run in the field. The components of a chilled-water central system include a chiller, air-handling units with chilled-water coils, chilled-water loop(s) with chilled-water pump(s), a condenser water loop, condenser water pump(s), and cooling tower.

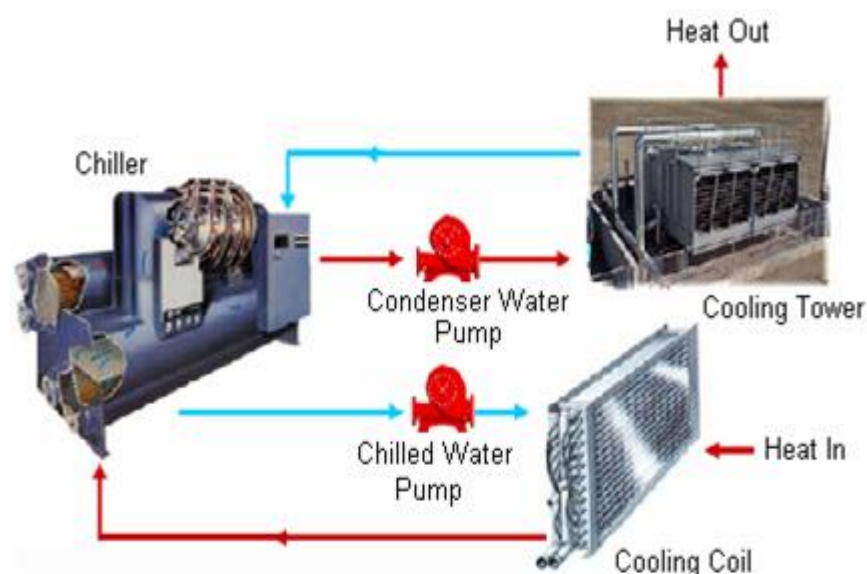


Figure 1.10 Chilled Water System

A central system is custom-designed for a building and is categorized by field assembly of:

- **Source components** – Comprising of the refrigeration compressor (reciprocating, scroll, screw or centrifugal type), shell and tube heat exchanger (evaporator) for chilled water production, shell and tube heat exchanger (condenser) for heat rejection in water cooled configuration, copper tube/aluminum finned condenser coil and fan (condensing unit) for air cooled configuration, an expansion valve between condenser and the evaporator. All these components are assembled in a skid, known as the chiller package. Refrigerant piping required to connect these parts is also enclosed in this skid. The chiller package is located in a dedicated plant room.
- **Distribution system** comprising of chilled water & cooling water pumps, air handling units, and ductwork. The pumps are generally located in the chiller plant room and the air handling units are installed in separate air handling rooms distributed at various locations of the building.
- **Terminal elements** comprising of grilles, diffusers, ventilation systems, and a number of elements adjusting comfort (local re-heat, humidity treatment, thermostats, air filtering etc.). Heat rejection system (cooling tower/s or air cooled condensers) are located outdoors.

All these components are field assembled. They perform all the functions as usual similar to a typical refrigeration system; however, all these parts are larger in size and have higher capacities.

### **1.6.2.1 Subsystems of Central Air Conditioning System**

Chilled water central system is broken down into three major subsystems: the chilled water plant, the condenser water system (or heat rejection system) and the air-delivery system.

#### **1.6.2.1.1 Chilled Water System**

The chilled water system supplies chilled water for the cooling needs of all the building's air-handling units (AHUs). The system includes a chilled water pump which circulates the chilled water through the chiller's evaporator section and through the cooling coils of the AHUs. The system may have primary and secondary chilled water pumps in order to isolate the chiller(s) from the building: the primary pumps ensure constant chilled water flow

through the chiller(s), while the secondary pumps deliver only as much chilled water is needed by the building AHUs.

Three most common chillers options are - reciprocating compressors (up to 200 TR), screw compressors (100 to 750 TR) and centrifugal compressors (200 to 2000 TR). The centrifugal compressors offer the best peak load efficiency while screw chillers give better part load and the off-design performance.

### 1.6.2.1.2 Condenser Water System

A refrigeration system must also reject the heat that it removes. There are two options for heat rejection: 1) air cooled and 2) water cooled.

- **Air cooled units** absorb heat from the indoor space and rejects it to ambient air. Air cooled units incorporate a condensing unit comprising of condenser, compressor, propeller fans and controls assembled in one unit and located outdoors. The Figure 1.11 shows a conceptual view of chilled water air-conditioning system with air-cooled condenser. The Figure depicts that heat is extracted from the space and expelled to the outdoors (left to right) through 4 loops of heat transfer. The chilled water is produced in the evaporator of the refrigeration cycle and is pumped to a single or multiple air-handling units containing cooling coils. The heat is rejected through an air-cooled condensing unit in the rightmost loop. These are the most common system used in residential and light commercial applications.

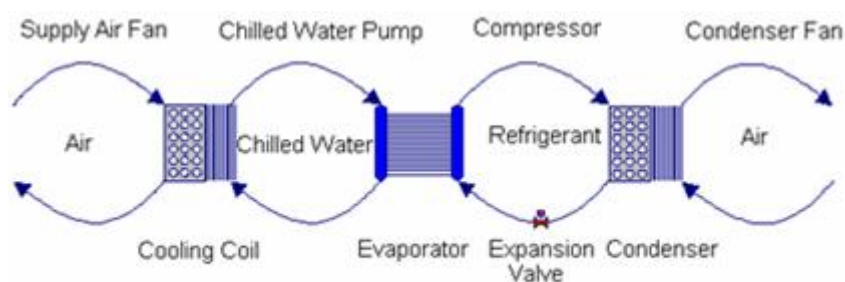


Figure 1.11 Chilled Water System with Air Cooled Condenser

- **Water cooled units** absorb the heat from the indoor space and rejects that heat to water which in turn may either reject heat via fluid coolers or cooling towers, or dry air coolers with adiabatic kits. The Figure 1.12 shows a conceptual view of chilled water air-conditioning system with water-cooled condenser and cooling tower. Here the heat is extracted from the space and expelled to the outdoors (left to right) through

5 loops of heat transfer. The chilled water is produced in the evaporator of the refrigeration cycle and is passed through a single or multiple cooling coils. The heat is rejected through a water-cooled condenser and the condenser water pump sends it to the cooling tower. The cooling tower's fan drives air across an open flow of hot condenser water, transferring the heat to the outdoors. Due to the lower refrigerant condensing temperatures compared to air cooled systems, water cooled chillers have higher coefficient of performance (COP). These are most common where good quality water is available and for large buildings such as multistory offices, hotels, airports and shopping complexes.

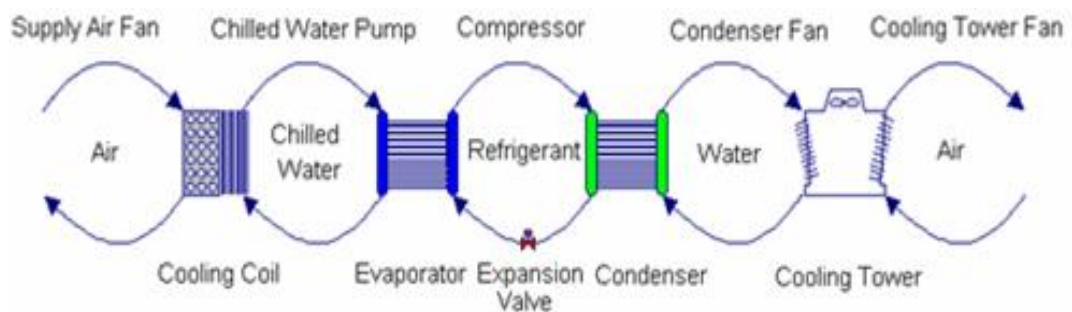


Figure 1.12 Chilled Water System with Water Cooled Condenser

### 1.6.2.1.3 Air Delivery System

Air is drawn into a building's Air conditioning system through the air intake by the air handling unit (AHU). Once in the system, supply air is filtered to remove particulate matter (mold, allergens, and dust), heated or cooled, and then circulated throughout the building via the air distribution system, which is typically a system of supply ducts and registers. In most buildings, the air distribution system also includes a return air system so that conditioned supply air is returned to the AHU ("return air") where it is mixed with supply air, re-filtered, re-conditioned, and re-circulated throughout the building. This is usually accomplished by drawing air from the occupied space and returning it to the AHU by: 1) ducted returns, wherein air is collected from each room or zone using return air devices in the ceiling or walls that are directly connected by ductwork to the air-handling unit; or 2) plenum returns, wherein air is collected from several rooms or zones through return air devices that empty into the negatively pressurized ceiling plenum (the space between the drop ceiling and the real ceiling); the air is then returned to the air-handling unit by ductwork or structural

conduits. Finally, some portion of the air within is exhausted from the building. The air exhaust system might be directly connected to the AHU and/or may stand-alone.

### **1.6.2.2 Central Air Conditioning System Types**

The Central system category could be further broken down into the following:

- Central systems with CAV air-handling units
- Central systems with VAV air-handling units
- Central systems with fan-coil units (All- Water systems).

#### **1.6.2.2.1 Constant Air Volume (CAV) System**

It is an all-air system which accomplish cooling and heating by varying the supply air temperature and keeping the air volume constant. The system works well and maintains comfortable conditions in spaces with uniform heating and cooling requirements.

#### **1.6.2.2.2 Variable Air Volume (VAV) System**

It is an all air system which can satisfy the individual cooling requirements of multiple thermal zones. This is achieved by supplying air at a constant temperature from central plant to one or more VAV terminal units in each zone and adjusting the amount of supply air to meet required cooling loads. The primary benefit of VAV over constant volume systems (CV) is its ability to simultaneously provide the required level of cooling to any number of zones within a building.

#### **1.6.2.2.3 All-Water Systems**

Central all-water systems with fan-coil units use un-ducted arrangement. Here chilled water is pumped from the central plant through pipes to the fan coil terminal units placed inside the conditioned space. The room air is re-circulated through the unit and is cooled by the coil. Fan coils are available in a range of sizes, but can be broadly divided between the perimeter under-window console type and ducted units generally installed in a ceiling space.

In commercial workplaces the comfort, safety and productivity of the occupants is affected by performance of air conditioning systems, which has indirect cost implications. There are

several choices for the type of air conditioning systems, each satisfying the air conditioning objectives with different degrees of success. Air conditioning systems with completely different design concepts or under different classification headings can co-exist in the same building. Such complication does not alter the fact that all systems generally have the same basic components responsible for the same thermo fluids or psychometric duties.

### **1.7 Air conditioning systems in India—State of the Art**

Before proceeding with the analysis it is worth stating the experience of using air conditioning systems and the development of the air conditioning system market in India. At the moment, the air conditioning system status in India is high. Air conditioning systems, with vastly different capacities and specifications, have established themselves in a wide range of applications. The market of air conditioners in India has been on a steady growth ever since, apart from certain exceptions. The perception of people towards the category of this product has witnessed a paradigm shift over the years from a luxury product to becoming a necessity in hot humid weather conditions of India. Increasing demand by the residential sector owing to reduction in prices has instigated the manufacturers to aim for a higher market share in the highly potential market of air conditioners in India. The demand from the commercial segment is catching up fast with the increasing number of commercial offices, stores and business apartments being set up, as compared to the demand from the residential segment.

According to "India Air Conditioner Market Forecast & Opportunities, 2017" the air conditioner market is poised for greater growth over next five years. India air conditioner market is forecasted to grow at a CAGR of 13.6% for the next five years. Increasing disposable income, rising weather temperature, falling prices of air conditioners coupled with the latest technological innovations increasing the cooling efficiency and the increasing commercialization of the economy are the factors which are driving air conditioners market in India [6]. The size of the room Air-conditioners industry is estimated at 1.1 million in volume terms, and Rs 24 billion in value terms. According to FICCI, Indian AC industry which is mainly dominated by players like Carrier and Voltas has been taken over by the new MNCs in the last few years. AC market is dominated by four major players—LG, Voltas, Carrier and Samsung. LG is the market leader with a market share of 29 per cent followed by Voltas (11) and Carrier and Samsung (9.2 each) in addition to other players like Hitachi and

Videocon [7]. The list of major player/manufacturers of air conditioning systems in India is given in the Table 1.1

Table 1.1 The list of major player/manufacturers of air conditioning systems in India

<b>Company</b>	<b>Brands</b>
Mirc Electronics Limited	Onida
Videocon International Limited	Videocon
LG Electronics India Limited	LG
Samsung India Electronics Limited	Samsung
Whirlpool of India Ltd	Whirlpool
Godrej & Boyce Mfg. Co. Ltd.	Godrej
Voltas Limited	Voltas
Electrolux Kelvinator	Electrolux
Blue Star India Ltd.	Blue Star
Daikin Industries, Ltd.	Daikin

### **1.8 Objectives and proposed methodology**

One of the most important tasks in the early stages of air conditioning system design is to determine the appropriate air conditioning system configuration. The configuration of air conditioning system includes the decision of system type, the selection of components and the choice of control strategies. The configuration has to match the characteristics of the building, its usage and occupancy, and the climate in which it is situated. The configuration also has to make use of the available resources, and eventually fulfill the requirements of the design. The designer would also have the objectives such as delivering high quality indoor environment with minimum cost and environmental impact. The first step of choosing a configuration for an air conditioning system design, however, is to identify the alternative solutions. The alternatives can then be evaluated and improved; and consequently the best solution that suits the design requirements will be chosen. As the final choice is only made among the identified alternative solutions, the strategy of identifying alternatives becomes dominantly important.

For almost every air conditioning system design project, there is more than one alternative configuration that would meet the design requirement. Also, among the globe, due to the rapid increase in the number of air conditioning systems and air conditioner manufacturers, the selection of air conditioning system for particular application and selection of best alternative air conditioning configuration to meet the design requirements has become a difficult task for user as well as designer of air conditioning system. The performance is the very important criteria for the selection of air conditioning system. But also there are many other parameters such reliability, quality, availability, environmental aspects, cost, etc. which are important during the selection of air conditioning system. Only few models are found in literature which considers few parameters for the selection of air conditioning system. So there is a need of the particular approach for selecting the optimal air conditioning system from the given alternatives. Multi-Attribute Decision Making (MADM) approach is a useful tool in the selection and evaluation of a system taking into consideration of large number of parameters [37-39 ].

Also, several models have been developed in order to study the integrated system as well as the interaction between the different parts of the air conditioning system. Some tools focus on the design and operation of the air conditioning system and other are converged towards a particular subsystem oriented design. So, it is realized that approaching the system as a whole is absolutely indispensable in order to acquire a better picture of the operation of every system component and the interaction between them.

Based on the above requirements, the objectives of this thesis are:

1. To develop a methodology by which design, evaluation and selection of air conditioning system can be made comprehensive and easy, considering various factors affecting the selection.

In order to achieve the above objective, the system approach named “**Technique for order preference by similarity to ideal solution (TOPSIS) – a Multi-Attribute Decision Making approach (MADM) approach**” is proposed, which includes:

- i. Identification of attributes of air conditioning system under various subsystems affecting the overall system.
- ii. Development of n-digit coding scheme to collect the information about the each attribute.

- iii. Development of TOPSIS procedure for attribute based evaluation, comparison, design improvement and ranking of feasible alternatives.
  - iv. Final stage selection considers all aspects which have not been considered during evaluation and ranking procedure and Force Field Analysis is proposed for this purpose.
2. To develop an integrated systems model for the structural analysis of air conditioning system, which integrates the different constituents of the air conditioning system and describe the whole system while taking into account the effect of interaction between these constituents for the better understanding of the structure of the air conditioning system.

In order to achieve this objective, the system approach named “**Graph Theoretic approach**” is implemented, which includes:

- i. Identification of different components or subsystems constituting the air conditioning system.
- ii. Identification of interactions between these different components.
- iii. Representation of components and their interactions by graph
- iv. Development of matrix models and the variable permanent function models to carry out decomposition, characterization, and the total analysis.

## **1.9 Organization of the thesis**

The thesis is composed of five chapters:

**Chapter 1:** In this chapter the history and need for air conditioning is described, together with an overview of the different choices for the type of air conditioning system. The scenario of air conditioning systems in India is also presented. Then, the objectives of this work, along with the proposed methodology, are presented.

**Chapter 2:** This chapter presents the extensive literature review of the related research work which has been done by different researchers in the past. This literature is divided into two categories: general literature review about the air conditioning system and the literature review about the system approach (MADM-TOPSIS and Graph Theoretic approach).

**Chapter 3:** In this chapter, system approach named Multi-Attribute Decision Making Approach along with TOPSIS is developed for the evaluation, comparison, ranking and optimum selection of air conditioning system. The various steps of this methodology, along with a suitable example, are described. The usefulness of this methodology is also presented in this chapter.

**Chapter 4:** This chapter is related to development of Graph Theoretic Approach for the modeling and integrative analysis of air conditioning system. The usefulness and various steps regarding development of this approach are presented. A case study of an existing central air-conditioning system in a library building located at Thapar University (Patiala), is presented to illustrate the effectiveness of the Graph Theoretical Approach.

**Chapter 5:** The conclusion of the thesis is presented in this chapter. A number of topics for future work are also provided in the end.

## CHAPTER 2

### LITERATURE REVIEW

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#### 2.1 Introduction

The scope of air conditioning is very wide and its applications are very diverse and literally Thousands of scientists and engineers have contributed towards its development. A substantial amount of work has been done on various aspects of air-conditioning Systems. This chapter covers the literature on development of various models, technologies and approaches for improving performance, design, efficiency, energy saving methods, reliability, durability, waste heat recovery methods, environmental protection aspects, choice of refrigerants and selection of different air conditioning systems. Literature survey also includes the review of system approaches used in the proposed work.

#### 2.2 Categorization of Literature

The literature is reviewed under following two distinctive categories:

1. General literature review about air-conditioning (component as well as whole system basis)
2. System approach ( MADM-TOPSIS and Graph Theoretic Approach)

##### 2.2.1 General Air Conditioning

**Piotr A. Domanski (1998)** prepared a conference report to summarize much of the material presented by various authors on different topics such as contemporary and future fluorochemicals, “natural” fluids, including hydrocarbons, carbon dioxide, and air, and secondary loop systems using ammonia and other chemicals. The conference provided a forum for presenting diverse views on possible responses to the ozone depletion and global warming problems. Author concluded that the task of selecting “the best” refrigerant for the 21st century will be difficult because the merits of different refrigerants result from a complex combination of several attributes; the most important being ozone depletion potential, system efficiency, direct global warming, safety, and cost. Because these attributes may carry different weights in different application and countries, the merits of the considered refrigerants are viewed with a corresponding lack of uniformity. Author also discussed that if refrigerant selection for the future is not affected by regulatory measures, it is safe to predict that HFCs will continue to be dominant for decades to come because of their

high efficiency, personal safety, and the current strong position in the market. He confirmed that the search for new and the refinement of mature technologies will continue in an effort to produce environmentally friendly solutions for the years to come.

**Sandy Halliday et al. (1999)** examined the feasibility of desiccant cooling in UK climates, using gas–solar hybrid technology for regeneration. The energy study reported by authors clearly demonstrated that it is feasible to use solar energy to power desiccant cooling systems in UK applications. Gaia Research worked with Napier University to develop computer codes for the simulation of solar energy collection and hot water delivery to drive the desiccant cooling system, based on real meteorological data. A solar desiccant computer model was developed with the University of Leeds which analysed the energy consumption and costs associated with desiccant cooling using meteorological data for an inner London site in 1994.

The paper concluded the following points:

- That inclusion of a 'solar' heater into the desiccant cooling cycle can lead to significant savings in primary energy consumption and associated CO<sub>2</sub> emissions.
- As desiccant cooling is an open cycle, solar energy can only be used effectively where the supply air volume flow rate is small. This effectively limits its application to installations where the bulk of the sensible cooling system is undertaken using a water based system.
- In applications where the bulk of the sensible cooling is being performed by water based systems, it may be necessary to supply larger than normal fresh air volume flow rates, in order to perform the required degree of latent cooling. Supply volume flow rates in the order of 1.8 l/s per m<sup>2</sup> of floor area should be acceptable for most applications.
- The regeneration air temperature should be kept as low as is practically possible, in order to minimize fossil fuel energy input.

**Malcolm R. Stout Jr. & James W. Leach (2002)** have evaluated the economics of alternative cooling tower capacity control methods. Annual fan electrical energy requirements are calculated for towers with single-speed, two-speed, and variable-speed fans. Fan energy requirements are determined counter-flow and cross flow towers designed for low initial cost and for energy efficiency. Effectiveness- NTU equations are solved to predict cooling tower performance with the fan running at various speeds. Natural convection, which

determines the cooling capacity when the fan is off, is accounted for using a mean enthalpy difference. Ambient conditions are simulated using typical meteorological year data for five locations.

Calculations based on typical meteorological year data have shown that fan energy savings for alternative capacity control methods do not depend strongly on the approach temperature, but are dependent on the range in colder climates. In colder climates, the potential savings increase by 25 percent to 40 percent when the range increases from 10°F to 40°F. The potential for saving is greatest for cooling towers designed for low initial cost, and is generally higher in locations where the wet bulb temperature remains relatively constant throughout the year. Authors also described that there is less potential for savings in cross-flow towers than in counter-flow towers. Also, the potential savings are lower when the cooling tower is oversized, or when the plant operates one shift instead of three shifts. It is suggested that the two-speed fans that can run at half speed are generally more suitable for low cost cooling towers at moderate loads and two-speed fans that can run at 2/3 speed are a better choice for energy efficient towers in most locations, especially at higher operating loads. At nominal conditions of approach = 7°F and range = 10°F, the potential savings are highest in locations where the wet bulb temperature remains close to the design value through much of the year. It is shown that the potential energy savings at nominal conditions in Los Angeles were about 50 percent higher than the savings in Columbus, Ohio.

**C. Lertsatitthanakorn et al. (2002)** investigated the cooling and dehumidifying performance of a lab-scale free convected ceiling type free convected Thermoelectric (TE) Air Conditioner (TEAC) experimentally. Tests were conducted for various operating conditions using two well insulated chambers of different volume, namely 0.024 and 1 m<sup>3</sup>. The whole set-up was slightly inclined (5") from the horizontal plane to collect the condensed water at the cold fins and to accelerate the downward airflow. It was found that the cooling performance of the system depended, as with the forced type TEAC, on the electrical power supply and the mass flow rate of hot air. Under the design conditions used here, suitable operating conditions were 3 amps and 0.027 kg.s<sup>-1</sup>, respectively. The corresponding cooling capacity was 169 W and the average chamber temperature varied between 16°C and 28°C, depending on the volume of the chamber. The amount of condensed water from the 1 m<sup>3</sup> chamber during 3 hours of operation was 14.6 g. When operated with open space, the TEAC could condense 356 g of water per 24 hours. Thus, it is found that the slightly inclined (ceiling) configuration was

found to be more efficient than the vertical (wall) configuration. Also, this concept found to be appropriate for either limited cooling capacity or dehumidifying large room spaces.

**Shabbir H. Gheewala and Per H. Nielsen (2003)** compared individual (split) and central systems of air-conditioning in a life cycle perspective, taking into account the environmental impacts and resource consumption during resource extraction, material production, production of the air conditioning units, their use, disposal and recycling using a tool namely Life cycle assessment (LCA). The performance of the central and individual air-conditioning systems was compared with respect to environmental impact and resource consumption, in order to identify the most sustainable solution for room cooling. The LCA study revealed that, on the whole, central systems were found to be superior to individual ones on all environmental counts considered. The central system was found to have about 35% lower acidification, nutrient enrichment and photochemical ozone formation potentials than individual systems; 96% lower stratospheric ozone depletion potential and 40% lower GWP. The central system consumes less energy carriers than individual systems whereas it consumes more water. Some metal consumptions were higher for central systems others were lower. Selling cool air instead of air conditioners in areas where the central system is feasible could help overcome the initial higher costs of central systems. This would help to realize the environmental and economic advantages of central systems and would reduce material consumption.

**H. Han and S. M. Deng (2003)** developed a novel residential clothes dryer using waste heat rejected from a room air conditioner. An experimental rig has been set up and extensive experimental work under various operating conditions carried out. A simplified mathematical expression (SME) for the clothes drying process using rejected waste heat from a RAC has also been developed and validated by the experimental results. The study results demonstrated that the use of heat rejected from a RAC for residential clothes drying in tropical or subtropical regions, where air conditioning season may last for 7–8 months, can achieve both effective clothes drying and energy use reduction. Authers have also given suggestions on future product development of the dryer and its large-scale application in residential buildings, particularly in high-rise residential buildings in highly-dense urban areas.

**Michael K. West and Glenn C. Haynes (2003)** presented a field test study of a two-wheel, gas-fired desiccant air conditioning system installed in a commercial building. Author's modeling, simulation, and actual metering study found that the desiccant system did decrease humidity and increase ventilation in the building, but that the desiccant unit delivered less cooling and less dehumidification capacity than the manufacturer's rating. He also determined that the desiccant system operation could be improved by about 25 percent as a result of optimization and field commissioning.

**David MacPhaul (2003)** presented a basic introduction to the problem of moisture buildup and dehumidification in a building in a humid climate. Author also discusses building pressurization problems, and shows how they can result in moisture buildup and make the dehumidification problem even worse. His case study of a hotel in South Florida with a negative pressure in several zones is a graphic illustration of the mold growth problems that can occur in very humid climates.

**Charles J. Cromer (2003)** presented a set of results from laboratory and field testing of two "energy saving" products and a desiccant-based HVAC system. The desiccant system—using the Cromer cycle—was specially constructed by modifying a standard residential-sized air conditioning system, and was metered and monitored while operating in an occupied residence. This Cromer cycle air conditioner effectively doubled the moisture removal of the basic air conditioner, and did not increase the operation cost above that of the basic air conditioning unit.

**Esam Elsarrag et al. (2005)** investigated experimentally the effect of different design parameters on the performance of a structured packed liquid desiccant-evaporative cooling system using Tri ethylene glycol (TIG). The performance has been assessed in the comfort zone, and design guidelines have been reported for humid and moderate climates. The effect of air and liquid flow rates, air humidity, and the desiccant vapor pressure have been reported on the humidity effectiveness, humidity ratio reduction, and the wet-bulb temperature reduction of the column. Theoretical and experimental studies of the simultaneous heat and mass transfer between air and desiccant in a packed absorption tower were conducted. Cellulose rigid media pads were used as structured packing, and different layers of the pad were oriented in a zig-zag manner so as to minimize TEG carryover. It has been found that

high liquid flow rates do not have a significant effect on the system performance if the liquid to airflow ratio exceeds the value of 2.

The theoretical model was compared with the experimental results and the effect of dehumidification on evaporative cooling performance was carried out. A reduction of 4.5°C to 9°C in the wet-bulb temperature was obtained from the dehumidifier. Design guidelines have been written to help in designing such systems.

**Yaw-Shyan Tsay et al. (2006)** studied experimentally the conventional desiccant air conditioning system under hot and humid climatic conditions and suggested it as suitable system to improve indoor air quality (IAQ) based on its superior humidity control. In this paper, the possibilities and methods of combining a desiccant cooling system with a CO<sub>2</sub> heat pump to improve overall energy efficiency and provide a steady heat source are also studied. When the exhaust heat generated from the CO<sub>2</sub> heat pump was used instead of an electric heater and the indoor air state was maintained within the comfort zone, the COP based on energy consumption improved from 0.6 to 1.8. This is a very substantial increase in energy efficiency. Study shows that COP for the proposed system is lower than for a conventional air-conditioning system, but considering the advantages in terms of IAQ improvement and maintenance fee saving, this system has been considered to be highly applicable in practice.

**Clito F.A. Afonso (2006)** has presented the main trends on air conditioning systems and classification of these cooling systems is done according to the final energy used to operate them. They are related with the research of new refrigerants that are environment friendly, with the development of new thermodynamic cycles namely the desiccants and hybrid and by the development of rotating devices to enhance the heat and mass transfer. This work is a review of cooling systems discussing both classical and more advanced technology emerging from recent research, with a respect to their general operating principles and their applications. Special attention was also given to refrigeration systems that can use solar energy turning them more sustainable. At last author concluded that an increase in efficiency, with lower costs, will allow for the diffusion of air conditioning systems in countries where they are not widely spread. Also the previsible decrease in dimension and costs of new systems will have benefits in the increase of competitiveness of the air conditioning industry.

**Qiu Haitao et al. (2006)** discussed the design process of a whole-new green air-conditioner with emphasis on the issues such as high-efficiency, energy-saving, and environmental friendly air-conditioning. This air-conditioner fully makes use of natural energy, taking the water as the refrigerant, using the air as medium. It does not use the compressor and any CFC refrigerant. Also it does not use chemical refrigerant. So it is the green air-conditioning product. The proposed product could be used with the conventional air-conditioner alternately. In morning, evening and the transition season, natural wind could be fully used to reduce the temperature in the room.

It has small volume, little weight, steady ventilation, slow wind speed, the low noise, the low consumption of water, the long life span of use, the simple structure, easy installation, and has easy maintenance. This success development of green air-conditioner made everyone know again the traditional pattern of energy use and it has good social benefit and economic benefit.

**CAO Guoqing and TU Guangbei (2006)** used grey relation analysis (GRA) to evaluate and select the air conditioning cold/heat source, considering sixteen main factors of four main categories such as technology, economy, reliability, and operation and management in selection procedure. Case study presented in paper showed that the result for selecting AC cold/heat sources with the GRA method can be more reasonable and convincing. It is concluded in the paper that the Gray relation analysis method is applied to assessing and selecting AC cold/heat sources of an actual building and the results indicate the effectiveness of this method. Also the principle and algorithm of this method are simple, so it can be easily programmed, which is helpful for application and generalization.

**W. L. Tse and Albert T.P. So (2007)** discussed the importance of human productivity to air-conditioning control in office environments. A case study was conducted to compare the performance of two control methods—conventional set point control and predicted-mean-vote-based (PMV-based) control—in an office environment. The comparison was based on three factors—human comfort, energy consumption, and human productivity. The set point control was only concerned with the first two factors, while the PMV control considered human productivity as well. Computer simulation techniques were employed to obtain the thermal environments created by the two control methods. The simulation results led to the comparison of human comfort and energy consumption. Then a financial analysis was developed in which the total financial loss under each simulated environment was derived to

reflect the performance in human productivity. More financial loss represented poorer performance in productivity. It was found that the conventional control caused significant reduction in human productivity even when an acceptable thermal comfort level was achieved in the office. Severe financial loss resulted, accounting for a 9% drop in net profit. On the other hand, the PMV control performed well for both human comfort and human productivity. Only a 0.4% profit drop was observed that compensated the extra energy consumption. Much better overall performance was yielded. Therefore, authors strongly recommended to consider human productivity in the design of future air-conditioning control as well as human comfort and energy consumption.

**Zhuang Wu et al. (2007)** developed a mathematical model to simulate airflow control systems of ventilation units. The presented Model-based analysis and simulation of the airflow control system of ventilation units is of primary importance for the design and maintenance of the entire HVAC system in building environments. Essential block components of the system are considered together with conventional PI controller implementations.

The dynamic responses obtained from simulations with mathematical models developed for each such a block have been compared with the measurement and experimental data. The performance of the constant airflow control scheme is analyzed and the results of the simulations for two typical loading conditions for the ventilation units installed in building environments are provided. The obtained results showed that the designed control system is flexible enough to satisfy all the imposed constraints with varied operating and loading conditions in order to fulfill the thermal comfort requirements for the extract air from the room and supply air to the room.

**Ahmed Hamza H. Ali et al. (2008)** investigated experimentally the effects of real fouling material at the air side of the evaporator's heat exchanger coil on the performance of room air-conditioner units as well as the impact of some fouling material compositions on indoor air quality. At the end of the experiments, examination of the biological contents of the fouling material on the coil was performed; it was found that the coil frontal face had heavy colonies of *Aspergillus* fungi of different species. This result is important to fill in the knowledge gaps between biological deposition, colonization, and expected health problems of occupants staying in environments with fouled evaporators. The results of the effect of such fouling materials on the unit performance showed that the unit coefficient of

performance at the standard air face velocity of 1.53 m/s for a clean evaporator coil was 2.82. It decreased to 1.89 (67%) after injection of 100 g of fouling materials, dropped to 1.79 (63.4%) after injection of 200 g of fouling materials, and fell to 1.23 (43.6%) after injection of 300 g of fouling materials. The results demonstrated that the predominant effect of fouling is to cause significant degradation in room air-conditioner coefficient of performance.

**Mahendra Kumar et al. (2008)** presented a state space based complete dynamic multi-input multi-output (MIMO) model for a direct expansion air-conditioning system. The dynamic behavior of both refrigeration and air circuits was taken into account in this model, and the condensation of moisture in air was considered in the model to obtain a better representation of an actual system. Authors proposed a lumped parameter model which consists of a set of first-order ordinary differential equations derived for all internal variables of the system. These variables contribute directly or indirectly to the thermal comfort and energy consumption of the system. The accuracy of this model depends upon the accuracy of estimating the thermal load, heat transfer coefficient, bypass factor, etc. This is a limitation of this model that exists in general for mathematical approximation of any physical plant. The proposed model was validated through simulation and experimental studies. The air conditioning unit of a railway coach was taken as a case study for simulation and experimental validation. A performance evaluation function in the form of internal variables was also designed and computed for ON-OFF control. Experimental validation was done on an air-conditioning system with ON-OFF control on an Indian Railway passenger coach. The transient and steady-state responses for dry-bulb temperature and specific humidity of inside air were obtained from the model and an experiment. These were compared and found to be in good agreement. Based on the knowledge of system parameters and initial conditions, authors concluded that the model is easy to use, as it requires the solution of a set of first-order ordinary nonlinear differential equations. This model also can be exploited to design a feedback controller based on nonlinear control theory.

**R.G. Kapadia et al. (2009)** presented transient characteristics of split air conditioners that use R-22 and R-410A as refrigerants. The model used for the overall system simulation comprises compressor, capillary, condenser, and evaporator submodels. The condenser and evaporator were modelled using continuity, momentum, and energy equations over the space and time span, using the implicit finite difference approach. Both of the heat exchangers were assumed to be made up of microfin tubes, although a comparison of transient pressure

response with smooth tubes is presented in the paper. Authors used appropriate correlations for calculating the two-phase heat transfer coefficients, the liquid vapor slip, and the friction factors. A simulation program has been developed in the MATLAB (Mathworks 2004) environment linked with REFPROP for refrigerant properties. Based on the developed model, the transient characteristics of the split air conditioner were pressure, temperature, and mass flow response, using R-22 and R-410A. The temperature response was validated by conducting a psychrometric test on a split air conditioner, and the pressure response was validated with published experimental data. Initially, the transient pressure response for a split air-conditioning system using microfin tubes was compared with a system using smooth tubes. It was observed that both the discharge and suction pressure responses were about 15 faster for microfin tubes. Subsequently, the transient characteristics of R-22 and R-410A refrigerants have been compared in detail for the split air conditioner using microfin tubes. Although the suction pressure response follows a similar trend for both of the refrigerants, the discharge pressure for R-410A reaches the steady-state value 35 s later than the R-22 does. The condensing temperature for R-410A was found to be 2.7°C (36.86°F) lower than that of R-22 (for the same size condenser). The pressure drops for R-410A in the condenser and the evaporator were found to be lower than that of R-22. The total transient loss during start-up was found to be 18.5% for the R-410A system and 18.7% for the R-22 system. The R-410A system has a lower transient loss due to refrigerant migration. Authors suggested that it possible to reduce the transient losses by optimizing the sizes and designs of the heat exchangers.

**Honggi cho and Keumnam Cho (2009)** conducted several drop-in tests of microchannel evaporators using R-22 for evaluating the performance of prototype microchannel evaporators for the residential air conditioner. Five prototype microchannel evaporators were manufactured and tested in psychrometric calorimeter test facilities. Each evaporator was made with two parallel flow heat exchangers connected with several return pipes. The parallel flow heat exchanger had 41 microchannel tubes with eight rectangular ports. Performance comparisons were made between microchannel evaporators with and without hydrophilic coating to assess the effect on condensate on evaporator surface. It is concluded that the cooling capacities of prototype 2, with a flow area ratio of 73/58%, and prototype 3, with six return pipes, were larger than prototype 1 by 15% and 9%, respectively. The cooling capacity of prototype 4 with three rows was larger than prototype 1 by 14%. Major findings were summarized as follows:

- The flow area ratio and the number of return pipes had a great effect on the cooling capacity, while the effect of third row on the cooling capacity was relatively smaller than that of the flow area ratio.
- Both mass flow rate and drain weight showed a similar trend with cooling capacity, and the refrigerant-side pressure drop showed the opposite trend to the mass flow rate.
- Prototype 2, with a flow area ratio of 73% and 58%, showed the best cooling capacity. Both refrigerant-side and air-side pressure drops for prototype 2 were acceptable for the residential air conditioner.
- The EER of prototype 2 was 3.2, which is suitable for residential air-conditioning applications considering that the EER of the typical residential air conditioner is approximately 3.

**Risto Ciconkov & Zahid H. Ayub (2009)** described a brief historic perspective of transition from natural refrigerants to synthetic and now back to natural refrigerants such as ammonia, carbon dioxide, and hydro-carbons. The thermodynamic, physical and safety properties of ammonia along with its advantages and disadvantages are presented. And it is concluded that the main drawback about a free use of ammonia has been its toxicity but this negative aspect can be overcome with an intelligent planning, proper maintenance procedures and better training of personnel. The issue of global warming resulted in a much closer look at the usage of ammonia as an environmental friendly refrigerant and has prompted various research centers around the world embarking on advanced research on different aspects of ammonia refrigeration cycle.

Authors also reviewed the development of new and advanced types of heat exchangers, new electromotor technologies, new compressor oil types, new concept of ammonia systems for handling the safety aspects, and the air conditioning systems with ammonia water chillers. Also it is given that in large industrial systems where there is a need for low evaporating temperatures, Ammonia/Carbon Dioxide cascade systems are being proposed and installed. At last of the paper, authors concluded that the future of ammonia refrigerant has never been more prospective than today.

**Ramesh k. shah (2009)** made a comprehensive review of automotive air conditioning systems. After discussing the basic operation of the A/C system, a brief summary is provided on historical development of the vehicular A/C system, with refrigerant history from the

inception of the A/C system to future systems. Starting with the historical developments, the evolution of major components of the A/C system is provided. These components are compressors, condensers, evaporators in HVAC modules, and expansion devices. A number of alternate refrigerants have been proposed by various industries to replace R134a for reducing the global warming potential from 1430 to below 150. A brief description of these refrigerants is provided for their characteristics and its impact on the A/C system and global warming potential while maintaining the current performance levels. Two alternative refrigerants left for consideration/implementation by January 2011 are R1234yf and CO<sub>2</sub>. Finally, briefly presented are alternatives being considered to reduce the A/C load in the passenger cabin. These alternatives would reduce the compressor power and hence the impact on the fuel consumption. Significant improvements have taken place from the dawn of mass production of A/C systems in 1954, and now even more innovative approaches are being considered worldwide to reduce the heat load in the passenger cabin and subsequent A/C system performance reduction without sacrificing human comfort and safety. Reduction in cost and better functionality and durability/reliability are also being worked on continually.

**Liu Jiayou and Zhao Yanxin (2009)** presented a paper which intends to use value engineering method (technical-economic comparison method which combines the technical and economic characters of villa air conditioning system schemes) to select air conditioning system for a villa. According to the principle of value engineering, a mathematical model for selection of villa air-conditioning system was constructed. The model mainly deals with the function analysis of villa air-conditioning system and formulated a value engineering method to evaluate villa air-conditioning system schemes. Value index which combined the technical and economic characters of schemes is used as an evaluation parameter to select the optimal scheme. It is mentioned in the paper that value engineering is a scientific technical-economic comparison method and application case shows it is feasible to select air-conditioning system scheme for villa using value engineering method. The evaluation method is simple and the result is intuitive.

**Xiaoping Feng and Zhifang Gu (2009)** have made an effort to investigate an internet-based decision-making method in selection scheme of cooling and heating source applying grey optimization method. Six indexes including initial investment, energy consumption, running cost, life period and reliability, equipment room area, influence to environment are considered as evaluation indexes. Authors discussed the programming design of dynamic

webpage and Active Server Pages (ASP), and studied the establishment and usage of network data base. Grey optimization model is constructed for determination of the best cooling and heating source scheme considering the multi-factors. The main advantage mentioned in this paper is that the specimens are not required to distribute specially. Practical examples show that it is a multi-factors relative analysis method which can be applied widely in decision making system.

**Changxing Zhang and Songtao Hu (2010)** have applied the Fuzzy Multi-Criteria decision-making (FMCDM) model for the optimal selection of cooling and heating sources for air conditioning systems, considering initial investment, annual operating expense, cycle life and reliability of different schemes and environmental protection impact as evaluating factors. Authors concluded that this model hurdles difficult problem for traditional ways to select optimal scheme and colligates some objects, which conquers shortsight decision and unilateral decision. For air-conditioning system, the model provides the references for schemes' optimization and insures the realization of energy-savings and green sustainable development.

**Bing et al. (2010)** have considered primary energy ratio as the criterion to select and evaluate the residential central air conditioning scheme for a particular application. Example of six residential central air conditioning schemes for a particular existing building is taken in the paper. The results showed that the primary energy ratio of water loop heat pump system is the maximum (which will be the optimal AC system scheme for the residential buildings), the next is the ground-source heat pump system, and the smallest is the household gas-fired AC system. The utilization of household gas-fired AC systems may save electric power, but are not good to energy conservation. Authors also suggested the consideration of initial cost, operating cost, primary energy ratio, as well as environment protection during the selection of the residential central AC system scheme.

**Hui-qing LIU and Han-dong LIU (2010)** proposed a multi-attribute group decision making model based on General Induced Ordered Weighted Averaging Operators (GIOWA) for the selection of air conditioning cool/heat source considering six indexes such as advanced technology, total investment, space index, operation and maintenance, environmental impact, safety and fire as evaluation indexes. The study outcomes showed that the method can effectively help one to make more reasonable decisions on the condition of decision makers can only provide less information with forms of ambiguous language. At the same time, the

model is simple and clear ideas, and is very suitable for solving the fuzzy qualitative indexes of multi-attributes group decision making, provide a workable solution with everyone.

**S. C. Kaushik et al. (2011)** proposed the idea of utilizing the waste heat from the industrial refrigeration and air conditioning system for drying or food processing sector by simply introducing a Canopus heat exchanger with existing system. There is a considerable amount of low-grade heat available in large-capacity systems. To recover this low-grade heat, it is suggested to introduce a Canopus heat exchanger between compressor and condenser components. The system feasibility is studied with various operating parameters and its effect on heat recovery factor and overall COP of the system. It is shown that this CHE, in spite of increasing overall COP of the system, does not affect the COP of system. Hence, heat recovery through Canopus heat exchanger is feasible and can be maximized by selecting optimum water flow rate, inlet water temperature, suitable operating conditions, and working fluid. Also the parametric results obtained for different eco-friendly working fluids, such as R-134a and R-507a, have been presented. It is also concluded that for the same operating conditions, the R-134a yield better performance as compared to R-507a. The Canopus heat exchanger options for heat recovery for low evaporator temperature R-134a giving higher heat removal factor whereas R-507a giving higher heat removal factor at higher temperature.

## **2.2.2 System Approach**

### **2.2.2.1 Multi-Attribute Decision Making (MADM)–TOPSIS**

**Ashish Bhateja et al. (1996)** presented a methodology for total design and evaluation of optimum spring based on multiple attribute decision making (MADM) approach, taking into account various design attributes at the conceptual stage of the design itself. Springs were first coded using a comprehensive attribute based three tier coded structure presented in the form of an algorithm. ‘Elimination search’ algorithm is presented for the rapid convergence of very large number to a manageable short-list of potentially suitable springs based on a few pertinent attributes. The short-listed alternatives are ranked on the basis of suggested merit index, by using a MADM method termed TOPSIS. At the last, it is concluded that the method is efficient and may easily be developed into an expert system for total design of springs, providing to be of immense use to the user and manufacturer alike.

**P.P. Bhangale et al. (2004)** have solved the robot selection problem which arises due increasing complexity, available features, and facilities offered by different robotic products. The objective of their research is to generate and maintain reliable and exhaustive database of robot manipulators based on their different pertinent attributes. That database can be used to standardize the robot selection procedure when the manufacturing firm has decided to use the robot for a particular operation. The methodology presented in this paper can help the robot user to save time by providing him a tool for selecting the robot system most suited for his operational needs. This paper presented a robot selection procedure based on the Multiple Attribute Decision Making (MADM) approach. Here by identifying 83 attributes of the robots, the attempt has been made to codify most of the robot characteristics, which will define the robot precisely and accurately. The coding scheme is illustrated with example of selecting a robot for some pick-n-place operation. It has presented the result of the information processing in terms of a merit value, which is used to rank the robots in the order of their suitability for the given application.

**R. T. Durai Prabhakaran et al. (2006)** described a methodology for evaluation, coding, ranking, and optimum selection of subsystems for composite product used directly by its manufacturers. The 77-attribute electronic coding scheme and the evaluation techniques are presented in this paper and are useful to the designer during all the phases of design process, and manufacturer for the selection of optimum subsystems, which meet global market requirements. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a Multiple-Attribute Decision Making (MADM) approach is used for selection of subsystems for a composite product development in order of preference for given application. Two graphical methods of MADM approach for evaluation and comparison are also introduced by the authors. It is recommended in this paper that manufacturer of composite product should develop attribute-based specification in the form of proposed coding scheme. This will directly help industry in carrying out SWOT (Strength– Weakness–Opportunities–Threats) analysis from the point of view of its manufacturing and business strategies.

**R.K. Garg et al. (2007)** presented a computational methodology for a computer-based solution to the problem of evaluation and selection of an optimum power plant. This methodology is named as multiple attribute decision making (MADM) methodology and consists of elimination search and technique for order preference by similarity to ideal solution (TOPSIS) approach. Authors have suggested a coding scheme based on 190

pertinent attributes for a given thermal power plant for the development of a large database of available plants, and their subsequent retrieval. The “technique for order preference by similarity to ideal solution” (TOPSIS) approach has provided a complete and thorough comparison and ranking of available power plants. Authors have also developed a user friendly computer software for Elimination Search and TOPSIS approach.

**C. Phaneendra Kiran et al. (2011)** presented a methodology useful in optimal selection of a mechatronic system based on the Mutli Attribute Decision Making (MADM) approach. Authors contributed in this paper by proposing a coding scheme which is a collection of 88 attributes which characterize a mechatronic system and is useful in differentiating mechatronic system alternatives. An illustrative example of selecting a hard disk drive (HDD), a mechatronic system, for the up-gradation of constumer’s office desktops is given to explain the methodology. Authors also identified 3-stage selection procedure, which includes elimination search, TOPSIS based evaluation and ranking, other graphical methods (linear graph and spider diagram), works on the information of the pertinent attributes. This procedure ranks the mechatronic system alternatives based on the Euclidian distance of alternatives from hypothetically best and hypothetically worst mechatronic systems.

#### **2.2.2.2 Graph Theoretical Approach**

**R.K. Garg et al. (2006)** developed a deterministic quantitative model based on graph theoretical methodology to compare various technical and economical features of wind, hydro and thermal power plants and also used to evaluate and rank the power plants in ascending or descending order in accordance with the value of their suitability index. It is concluded by the authors that the methodology present in this paper allows a decision maker to perform, not just a general analysis, but also other various focused analysis regarding his personal preferences.

**R.T. D. Prabhakaran et al. (2006)** developed an integrated systems model for the structure of the composite product system in terms of its constituents and interactions between the constituents and the molding processes, curing kinetics etc. using graph theory and matrix algebra. This proposed systems methodology for developing a composite product considered all attributes responsible for design, production, and process parameters. The composite product is first modeled with the help of graph theory, then by variable adjacency matrix and

then by a multinomial known as permanent function. The permanent function has provided an opportunity to carry out structural analysis of the composite product in terms of strength, weakness, improvement, and optimization by correlating the properties of a composite with its structure.

**Varinder Singh and V.P. Agrawal (2008)** have presented a methodology that builds a flexible and comprehensive model of manufacturing system, which has the capability to consider the interdependencies between its various subsystems. After the identification of elements constituting a manufacturing system and the interactions between them, it has been represented by graph-based model. Also the matrix models and the variable permanent function models have been developed to carry out decomposition, characterization and the total analysis. Structural patterns and combination sets of subsystems interacting in various ways have been recognized as capabilities of manufacturing system in different performance dimensions. The permanent function of the manufacturing system matrix has been proposed as a systematic technique for structural analysis of manufacturing system.

**C.P. Kiran et al. (2011)** presented a novel methodology which combines all the design aspects together to generate a useful form of solution for the mechatronic industry. This methodology concurrently considered all the x-abilities/design aspects along with interactions without missing any useful information and hence led to a high quality product. The methodology presented in this paper consists of graph theory, matrix algebra, and permanent multinomial. Eight x-abilities namely, miniaturization, intelligence, integration, environment, quality, reliability, manufacturing, and assembly for concurrent design of a mechatronic system and the design parameters under each x-ability are identified. Also a colour graph is proposed for visual analysis.

### **2.3 Gap Analysis**

From literature review it is seen that a substantial amount of work has been done on various aspects of air conditioning systems by different researchers such as development of various models, technologies and approaches for improving performance, design, efficiency, energy saving methods, reliability, durability, waste heat recovery methods, environmental protection aspects, choice of refrigerants and selection of different sub-systems as well as whole air conditioning systems. Much of the research carried out in the latest years has been concentrated on using less environmentally hazardous, natural and with better compatibility

with oils refrigerants for replacing mainly HFC's. Moreover, research continues in the areas of improving efficiencies of motors, compressors, fans, increasing the heat transfer in evaporators and condensers, minimizing losses, better humidity control using desiccant systems, economics of cooling towers, waste heat recovery systems, etc. In parallel to the air conditioning system technological amendment, research proceeds in all the areas regarding component development and system design and in comfort-providing systems. Since the literature reveals that the effect of individual parameters such as economic aspects of maintenance and operation, indoor air quality, environmental factors, energy saving techniques, etc. have been discussed by different researchers but all such factors have not been considered all together in a unified manner. Also the subsystems are considered independently in design or modeling of an air conditioning system without considering the effect of other subsystems as well as the interaction between them. Only the few researchers have considered the various sub-systems simultaneously in evaluation and optimum selection of air conditioning systems. In actual, modeling, evaluation and selection of air conditioning system depends on many attributes. It is reasonable to consider more factors including building architecture, technical, environment aspects, etc. for selection of air conditioning systems for particular application. An exhaustive list of attributes for air conditioning system is not available in the literature. Also, from the literature review, we can say that no one has considered a system approach that can take all the attributes that are mainly responsible for producing a air conditioning product system using optimum selection procedure and also no one has considered the structural constituents for analyzing an air conditioning system along with their interactions at conceptual and design stages, and also there is no methodology proposed for an integrated system approach for analyzing air conditioning systems.

From the literature review regarding system approach, one can see that the desired methodologies for optimum selection and for analyzing air conditioning systems, though seen in other different engineering areas, has not yet been developed for air conditioning systems. So there is a need to develop such methodologies and it is hoped that the system approach is useful tool and technique.

## CHAPTER 3

# EVALUATION, COMPARISON, RANKING AND SELECTION OF OPTIMUM AIR CONDITIONING SYSTEM

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### 3.1 Introduction

With the development of human society and economy, living standard of people is improving day by day, and higher living conditions are demanded. So, more attention is paid towards treating the indoor air to establish and maintain required standards of indoor air quality (IAQ) indexes such as temperature, humidity, air cleanliness, etc. Air conditioning system is used to improve IAQ. Apart from comfort air conditioning required for comfort of persons, air conditioning systems are also used to provide conditions that some processes require. These processes require certain air temperature and humidity for successful operation. Amongst the several methods employed for air conditioning, the most commonly used are air conditioning systems based on vapour compression and vapour absorption. There has been rapid increase in the number of air conditioning systems and air conditioner manufacturers. Air conditioning systems with vastly different capacities and specifications are available for a wide range of applications. The selection of air conditioning system to suit a particular application, from the large number of air conditioning systems available in the market today has become a difficult task. Also, in air conditioning system design, there are many forms and types of choice for air conditioning subsystems, therefore air conditioning designers often face problem during selection of optimum subsystems, which meet global market requirements with a variety of decision-making program. Therefore there is need of a mathematical tool in selection of an air conditioning system.

During selection process of an air conditioning system various sets of attributes are required by designer, manufacturer, maintenance person and end customer to get optimal results. There are number of reported studies concerning the selection of air conditioning system. Shabbir H. Gheewala and Per H. Nielsen [12], in order to identify the most sustainable solution for room cooling, compared the performance of the central and individual air conditioning systems with respect to environmental impact and resource consumption using a tool named Life cycle assessment (LCA). Clito F.A. Afonso [19] has presented the main trends on air conditioning systems. They are related with the research of new refrigerants that

are environment friendly. Also a classification of cooling systems is presented according to the final energy used to operate them. A. Qiu Haitao et al. [20] discussed the design process of a whole-new green air-conditioner with emphasis on the issues such as high-efficiency, energy-saving, and environmental friendly air-conditioning. Guoqing and TU Guangbei [21] used grey relation analysis (GRA) to evaluate and select the air conditioning cold/heat source, considering sixteen main factors of four main categories such as technology, economy, reliability, and operation and management in selection procedure. Liu Jiayou and Zhao Yanxin [29] presented a paper which intends to use value engineering method (technical-economic comparison method which combines the technical and economic characters of villa air conditioning system schemes) to select air conditioning system for a villa. Xiaoping Feng and Zhifang Gu [30] have made an effort to investigate an internet-based decision-making method in selection scheme of cooling and heating source applying grey optimization method. Six indexes including initial investment, energy consumption, running cost, life period and reliability, equipment room area, influence to environment are considered as evaluation indexes. Changxing Zhang and Songtao Hu [31] have applied the Fuzzy Multi-Criteria decision-making (FMCDM) model for the optimal selection of cooling and heating sources for air conditioning systems, considering initial investment, annual operating expense, cycle life and reliability of different schemes and environmental protection impact as evaluating factors. Bing et al. [32] have considered primary energy ratio as the criterion to select and evaluate the residential central air conditioning scheme for a particular application. Example of six residential central air conditioning schemes for a particular existing building is taken in the paper. CAO Hui-qing LIU and Han-dong LIU [33] proposed a multi-attribute group decision making model based on General Induced Ordered Weighted Averaging Operators (GIOWA) for the selection of air conditioning cool/heat source considering six indexes such as advanced technology, total investment, space index, operation and maintenance, environmental impact, safety and fire as evaluation indexes. In actual, selection of air conditioning system depends on many attributes. It is reasonable to consider more factors including building architecture, technical, environment and etc. for selection of air conditioning systems for particular application. An exhaustive list of attributes for air conditioning system is not available in literature.

Different attributes which influence the selection of air conditioning system at each phase of the process can be either quantitative or qualitative in nature. It is a very complex job to select an air conditioning system for a particular application based on the combination of

these attributes. The complexity of a problem raises more when there are over 173 attributes that have to consider in selection process. So there is a need to develop a system approach that can take all the attributes for evaluation and optimum selection of an air conditioning system. The proposed methodology used for selection of a product based on complex set of attributes is multiple attribute decision making (MADM) approach. This methodology is being applied in different areas like total design and evaluation of optimum spring by Ashish Bhateja et al. [35], specification, comparison and selection of robot by P.P. Bhangale et al. [36], selection of thermal power plants by R.K. Garg et al. [38], and the selection of electroplating waste treatment system by Abhishek kumar et al. [44]. From the literature review, we can say that no one applied the proposed user-friendly and MADM based selection methodology for an air conditioning system by considering its responsible attributes in totality. This chapter attempts to propose a technique for order preference by similarity to ideal solution (TOPSIS) - a MADM approach and graphical comparison techniques namely histogram, graphical and radar for evaluation and optimal selection of an air conditioning system for a particular application. It starts from the identification, classification and coding of the system attributes, then the selection procedure proceeds to evaluate and rank the certain shortlisted alternatives by employing the TOPSIS approach. The proposed 3-stage selection methodology is explained with the help of an illustrative example.

### **3.2 Identification of Attributes**

In global market, commercial air conditioning may be provided by a variety of equipment ranging from low horsepower self-contained systems to very large built-up central systems of several thousand ton capacity. User's ultimate objective is to acquire and utilize an air conditioning system that will provide the most appropriate performance on a whole of life basis, in terms of capital, replacement and maintenance costs. For instance residential apartments, shopping complex, office complex, hospital, hotel, airport or industry; all have different functional requirements, occupancy pattern and usage criteria. The geographical location of the building, ambient conditions, indoor requirements, building materials, dimensional parameters, aesthetic requirements, noise and environment issues need different treatment. Therefore, the optimum selection of an air conditioning system for a particular application is going to affect the overall performance of the system and at the same time the selection of air conditioning system is mainly dependent on its different attributes, e.g. efficiency, cost effectiveness and eco-friendliness, etc., which affect its performance

characteristics. It shows that, for evaluating and comparing the various alternative air conditioning systems, the proper identification of the system attributes is very much important. Selecting the best air conditioning system for a particular building must be carefully considered and researched by the consultant or engineer in close coordination with the architect, electrical and plumbing consultants and owners before freezing the basic air conditioning system and building layout. It is difficult for an engineer to select an air conditioning system for a given space and requirements. The designer has to keep in mind the fitness of the system to the space to be conditioned and the satisfactions of the customer. Above all, the economic consideration plays a vital role in selection of air conditioning system. So keeping all this in mind air conditioning system attributes based on its broad area as general parameters, building design aspects, system performance characteristics, etc. are identified. They are listed in Table 3.1. For example, Building design aspects affects the selection of air conditioning system in such a way that considerable space is needed for mechanical rooms to house the air conditioning system equipment. In addition shaft spaces are required for routing ducts/pipes and other services e.g. electrical and plumbing work. Inadequate spaces to run ducts, probably force the system designer to use decentralized or unitary air conditioning units. Also to assemble the best air conditioning system, the efficiency, performance, cost and energy use are major considerations when selecting components for the system. The cost of the energy consumed by the components of the air conditioning system is an important aspect of the system selection. Each component must use as little energy as possible and still meet the performance requirements. Availability of water also affects the selection of system because the places where water is scarce, the only choice leans towards air-cooled equipment. Similarly much more factors such as environmental constraints, type of ownership, system flexibility, life cycle costs, life expectancy, specifications of each component of air conditioning system, etc. must be considered before during the selection process.

Here, 173 pertinent attributes necessary for the life cycle design of the air conditioning system are identified, but the user, designer or manufacturer can add or delete some of the attribute depending upon their requirement. If the identification of air conditioning system attributes is done carefully, the selection of the air conditioning system for typical application will be precise, which will satisfy the user's requirements.

Table 3.1 Categorization of air conditioning system attributes:

Sr. No.	Name of attribute	
	<b>General</b>	equipment
1	Type of air conditioning system	26 Space for terminal equipment
2	Basic working cycle	27 Availability of drain lines in peripheral area
3	Application	<b>System Performance Characteristics</b>
4	Usage patterns	28 IAQ provided
5	Type of ownership	29 Overall Capacity
6	Cooling medium	30 Maturity of technology
7	Quality	31 C.O.P
8	Reliability	32 Type of refrigerant
9	Aesthetics	33. Load diversity
10	Availability	34. Useful life of the plant
11	Serviceability	35. Flexibility
12	Maintainability	36. Meeting requirements of Local regulations/codes
13	Robustness & Redundancy	37. System component efficiency
14	Visibility of controls	38. Air through
15	Warranty	39. Operating temperatures
	<b>Building design aspects</b>	40. Compatibility
16	Plant room space	41. Level of insulation
17	Adequate height	<b>Controls sub system</b>
18	Location of plant room	42 Type of control
19	Ceiling space availability for routing ducts	43 Type of automatic control
20	Space availability for routing pipes	44 Degree of automation
21	Space availability for installing AHUs	45 Control and operational requirements
22	Space availability for electrical work	46 Control complexity
23	Space availability for plumbing work	47 Control flexibility
24	Space availability for maintenance	<b>Environmental sub system</b>
25	Accessibility for installation of	48 Ozone depletion potential
		49 Global warming potential

Table 3.1 (continued)

50	Thermal pollution (Thermal discharge index)	75	BHP/TR at operating conditions
51	Acoustics	76	Lubrication
52	Vibrations	77	Type of prime mover
53	Outside air humidity	<b>Condenser Attributes</b>	
54	Temperature	78	Condenser type
55	Contamination	79	Shell diameter & length
<b>System economics</b>		80	Tube material
56	Unit cost (includes installation, construction, equipment cost etc.)	81	Fouling factor
57	Operating cost	82	No. of tubes
58	Equipment maintenance cost	83	Tube diameter (mm)
59	Plant replacement cost	84	Tube length (mm)
60	Fuel cost	85	Tube surface area inside
61	Cost of water	86	Tube surface area outside
62	Cost of refrigerant	87	No. of passes
<b>Physical</b>		88	Water flow (m <sup>3</sup> /hr)
63	Size of system	89	Condenser efficiency
64	Weight of system (Single unit)	90	Refrigerant capacity of condenser
65	Equipment layout	91	Maximum cooling capacity (Kcal/hr)
66	Piping layout	92	Operating weight (kg)
67	Ducting layout	<b>Chiller attribute</b>	
68	Operating voltage requirement	93	Chiller type
69	Frequency required	94	Shell diameter & length
70	No. of phases required	95	Tube material
71	Type of current	96	Fouling factor
<b>Compressor Attributes</b>		97	No. of tubes
72	Type of compressor	98	Tube diameter (mm)
73	Capacity at operating conditions	99	Tube length (mm)
74	Operating speed	100	Tube surface area inside
		101	Tube surface area outside
		102	No. of passes

Table 3.1 (continued)

103	Water flow (m <sup>3</sup> /hr)	128	Useful life of boilers
104	Chiller efficiency	129	Piping and pickup losses for boilers
105	Refrigerant capacity of chiller	130	Type of the fuel
106	Maximum cooling capacity (Kcal/hr)	131	Local availability of fuel
107	Operating weight (kg)	132	Comparative cost of fuel
<b>Chilled water &amp; condenser water pump attributes</b>		133	Fuel calorific value
108	Type of pumps	134	Specific fuel consumption
109	Pump capacity	135	Safety
110	Pump head	<b>Air handling and distribution attributes</b>	
111	Pump RPM	136	Type
112	Pumps efficiency	137	Capacity
113	Motor horsepower	138	Cooling medium
114	Useful life of pumps	139	Type of fan
115	Pumps rating	140	Fan speed
<b>Cooling and feed water attributes</b>		141	Fan motor horsepower
116	Availability of water	142	Wheel diameter
117	Water requirement	143	Fan housing and wheel material
118	Water flow rate	144	Rate of flow or capacity
119	Condenser inlet water temperature	145	Fan static pressure
120	Condenser outlet water temperature	146	Fan drive mechanism
121	ph of boiler (feed) water	147	Expected life of fan versus first cost
122	Boiler feed water temperature	148	Loudness of noise produced by fan
123	Condensate temperature	149	Outdoor air requirement for ventilation facilities
<b>Heating equipment attributes</b>		150	Cooling or heating coils
124	Source heating equipment	151	Type of air cleaning devices
125	Type of boiler	152	Filtration efficiency
126	Boiler capacity	153	Filtration capacity
127	Boiler efficiency	154	Type of ductwork
		155	m <sup>3</sup> of duct work

Table 3.1 (continued)

156	Type of air terminal unit	164	Cooling capacity of C.T.
157	Type of air supply devices	165	Motor power for C.T.
<b>Pipe attributes</b>		166	Rated water flow
158	Type of pipes and pipe fittings	167	Cooling range at rated flow m <sup>3</sup> /hr
159	Material of pipes	168	Evaporation loss at rated condition
160	Pipe size	169	Sump/Basin Capacity
161	Frictional losses	170	Operating Weight
162	Maximum pressure drop	171	Supply Voltage
<b>Cooling tower attributes</b>		172	Supply phase
163	Type of cooling tower	173	Construction/Material of C.T.

### 3.3 N – Digit Coding Scheme

To ensure effective and efficient use of proposed attributes for identification, classification, comparison, evaluation and ranking of an air conditioning system and to make this procedure user friendly, an n – digit coding scheme is developed. Such a 173 digit coding structure gives a complete attributes profile of the air conditioning system. Proposed coding scheme is illustrated in Table 3.2 for an application of packaged air conditioning system situated at Thapar University, Patiala. The first column represents the block number corresponds to the 173 attributes, the second column represents the name of the attribute, the third column represents information about the attribute in a particular application, and the fourth column represents the alphanumeric code based on the type of attribute. The classification of the attributes is done either quantitatively or qualitatively.

A compact coding structure has been prepared for the above application and is shown in Table 3.3. In this coding structure the code within the box is in format  $y_i/x_i$ ,  $i=1, \dots, n$ , where  $y_i$  is the block number and  $x_i$  represents the alphanumeric code allotted to the particular attribute. For qualitative, the coding is done on a grade scale. Some of the attributes are coded with alphabets. A numerical value is allotted to quantitative attribute. Numerical values of the quantitative attributes are allotted in scaled ranges 0-3, 0-5, 0-7, 0-9 etc. The proposed coding

scheme is illustrated here with examples. First example is for quantitative attributes. Suppose we are coding the useful life of the plant, it can be done as follows:

Useful life of system (in years)	Code
0 – 5	1
5 – 10	2
10 – 15	3
15 – 20	4
20 – 25	5
>25	6

This code will be used to specify the useful life of the plant in the respective block number 34, since it is allotted to it, as shown in Table 3.2. Here the air conditioning system under consideration has the useful life of 15 years, which can be given code 4.

Second example is for qualitative attributes. Suppose we coding the reliability of air conditioning system, it can be done as following:

Reliability	Code
Poor	1
Below average	2
Average	3
Above average	4
Good	5

Here the air conditioning system under consideration has good reliability, which can be given code 5.

In Table 3.2, the code '0' represents that the information relating to the particular cell is not available to the authors. This information is not provided by the manufacturer, but the authors feel that this information should be provided by the manufacturer to make the database exhaustive. Moreover, the database storage, retrieval and the selection procedure will be more precise and accurate. This coding scheme can be used for comparing two air conditioning systems critically and for better insight and understanding of the air conditioning system alternative or the subsystem or the components from the database.

Table 3.2 Example: Water-cooled packaged air conditioning system (model DPW1983R1) from company named “BLUE STAR” for an auditorium located at Thapar University, Patiala, India.

Block No.	Attribute	Information	Code
<b>General</b>			
1	Type of air conditioning		
	System	DX system	DX
2	Basic working cycle	Vapor compression	VC
3	Application	Auditorium Air Conditioning	A
4	Usage patterns	—	0
5	Type of ownership	Single	1
6	Cooling medium	Water	2
7	Quality	—	0
8	Reliability	Good	5
9	Aesthetics	Average	3
10	Availability	—	0
11	Serviceability	—	0
12	Maintainability	—	0
13	Robustness & Redundancy	Above average	4
14	Visibility of controls	Good	5
15	Warranty	—	0
<b>Building design aspects</b>			
16	Plant room space	—	0
17	Adequate height	—	0
18	Location of plant room	—	0
19	Ceiling space availability for		
	Routing ducts	—	0
20	Space availability for routing pipes	—	0
21	Space availability for installing		
	AHUs	—	0
22	Space availability for electrical work	—	0
23	Space availability for plumbing work	—	0

Table 3.1 (continued)

Block No.	Attribute	Information	Code
24	Space availability for maintenance	—	0
25	Accessibility for installation of equipment	—	0
26	Space for terminal equipment	—	0
27	Availability of drain lines in peripheral area	—	0
<b>System Performance Characteristics</b>			
28	IAQ provided	Good	5
29	Overall Capacity (5 units)	82.5TR	3
30	Maturity of technology	advanced	4
31	C.O.P.	—	0
32	Type of refrigerant	R-22	R22
33	Load diversity	—	0
34	Useful life of the system	15 Years	4
35	Flexibility	—	0
36	Meeting requirements of Local regulations/codes	—	0
37	System component efficiency	—	0
38	Air through	—	0
39	Operating temperatures	—	0
40	Compatibility	—	0
41	Level of insulation	Good	5
<b>Controls sub system</b>			
42	Type of control	Semi-Automatic	2
43	Type of automatic control	Closed loop	1
44	Degree of automation	%	4
45	Control and operational requirements	—	0
46	Control complexity	Average	3
47	Control flexibility	Average	3

Table 3.1 (continued)

Block No.	Attribute	Information	Code
<b>Environmental sub system</b>			
48	Ozone depletion potential	—	0
49	Global warming potential	—	0
50	Thermal pollution (Thermal discharge index)	—	0
51	Acoustics	below average	2
52	Vibrations	—	0
53	Outside air humidity	—	0
54	Temperature	—	0
55	Contamination	—	0
<b>System economics</b>			
56	Unit cost (includes installation, construction, equipment cost etc.)	Above average	4
57	Operating cost	Average	3
58	Equipment maintenance cost	Low	1
59	Plant replacement cost	—	0
60	Fuel cost	—	0
61	Cost of water	Average	3
62	Cost of refrigerant	—	0
<b>Physical</b>			
63	Size of system	—	0
64	Weight of system (Single unit)	605 kg	2
65	Equipment layout	—	0
66	Piping layout	—	0
67	Ducting layout	—	0
68	Operating voltage requirement	415V	3
69	Frequency required	50HZ	2
70	No. of phases required	3 phase	3
71	Type of current	DC	2

Table 3.1 (continued)

Block No.	Attribute	Information	Code
<b>Compressor Attributes</b>			
72	Type of compressor	Screw	S
73	Capacity at operating conditions	—	0
74	Operating speed	—	0
75	BHP/TR at operating conditions	—	0
76	Lubrication	—	0
77	Type of prime mover	—	0
<b>Condenser Attributes</b>			
78	Condenser type	Water cooled condenser	WC
79	Shell diameter & length	—	0
80	Tube material	—	0
81	Fouling factor	—	0
82	No. of tubes	—	0
83	Tube diameter (mm)	—	0
84	Tube length (mm)	—	0
85	Tube surface area inside	—	0
86	Tube surface area outside	—	0
87	No. of passes	—	0
88	Water flow (m <sup>3</sup> /hr)	—	0
89	Condenser efficiency	—	0
90	Refrigerant capacity of condenser	—	0
91	Maximum cooling capacity (Kcal/hr)	—	0
92	Operating weight (kg)	—	0
<b>Chiller Attributes</b>			
93	Chiller type	Finned type	F
94	Shell diameter & length	—	0
95	Tube material	—	0
96	Fouling factor	—	0
97	No. of tubes	—	0

Table 3.1 (continued)

Block No.	Attribute	Information	Code
98	Tube diameter (mm)	—	0
99	Tube length (mm)	—	0
100	Tube surface area inside	—	0
101	Tube surface area outside	—	0
102	No. of passes	—	0
103	Water flow (m <sup>3</sup> /hr)	—	0
104	Chiller efficiency	—	0
105	Refrigerant capacity of chiller	—	0
106	Maximum cooling capacity (Kcal/hr)	—	0
107	Operating weight (kg)	—	0
<b>Chilled water &amp; condenser water pump attributes</b>			
108	Type of pumps	Centrifugal	C
109	Pump capacity	—	0
110	Pump head	—	0
111	Pump RPM	—	0
112	Pumps efficiency	—	0
113	Motor horsepower	—	0
114	Useful life of pumps	—	0
115	Pumps rating	—	0
<b>Cooling and feed water attributes</b>			
116	Availability of water	Less	1
117	Water requirement	—	0
118	Water flow rate	—	0
119	Condenser inlet water temperature	—	0
120	Condenser outlet water temperature	—	0
121	pH of boiler (feed) water	—	0
122	Boiler feed water temperature	—	0
123	Condensate temperature	—	0

**Heating equipment attributes**

Table 3.1 (continued)

Block No.	Attribute	Information	Code
124	Source heating equipment	—	0
125	Type of boiler	—	0
126	Boiler capacity	—	0
127	Boiler efficiency	—	0
128	Useful life of boilers	—	0
129	Piping and pickup losses for boilers	—	0
130	Type of the fuel	—	0
131	Local availability of fuel	—	0
132	Comparative cost of fuel	—	0
133	Fuel calorific value	—	0
134	Specific fuel consumption	—	0
135	Safety	—	0
<b>Air handling and distribution attributes</b>			
136	Type	Horizontal	H
137	Capacity	—	0
138	Cooling medium	—	0
139	Type of fan	—	0
140	Fan speed	—	0
141	Fan motor horsepower	—	0
142	Wheel diameter	—	0
143	Fan housing and wheel material	—	0
144	Rate of flow or capacity	11213 CMH	4
145	Fan static pressure	—	0
146	Fan drive mechanism	—	0
147	Expected life of fan versus first cost	—	0
148	Loudness of noise produced by fan	—	0
149	Outdoor air requirement for ventilation facilities	—	0
150	Cooling or heating coils	—	0
151	Type of air cleaning devices	EU-2	E

Table 3.1 (continued)

Block No.	Attribute	Information	Code
152	Filtration efficiency	%	4
153	Filtration capacity	down to microns	4
154	Type of ductwork	G. I. Ducts	G
155	m <sup>3</sup> of duct work	—	0
156	Type of air terminal unit	—	0
157	Type of air supply devices	—	0
<b>Pipe attributes</b>			
158	Type of pipes and pipe fittings	—	0
159	Material of pipes	—	0
160	Pipe size	—	0
161	Frictional losses	—	0
162	Maximum pressure drop	—	0
<b>Cooling tower attributes</b>			
163	Type of cooling tower	Induced Draft	ID
164	Cooling capacity of C.T.	100 TR	3
165	Motor power for C.T.	5 HP	3
166	Rated water flow	—	0
167	Cooling range at rated flow m <sup>3</sup> /hr	—	0
168	Evaporation loss at rated condition	—	0
169	Sump/Basin Capacity	330 Gallons	3
170	Operating Weight	—	0
171	Supply Voltage	—	0
172	Supply phase	—	0
173	Construction/Material of C.T.	—	0

Table 3.3

Compact coding structure of Water-cooled packaged air conditioning system (model DPW1983R1) from the company named “BLUE STAR” for an auditorium located at Thapar University, Patiala, India.

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General	1/DX	2/VC	3/A	4/0	5/1	6/2	7/0	8/5	9/3
	10/0	11/0	12/0	13/4	14/5	15/0			
Building Design Aspects	16/0	17/0	18/0	19/0	20/0	21/0	22/0	23/0	24/0
	25/0	26/0	27/0						
System Performance...	28/5	29/3	30/4	31/0	32/R22	33/0	34/4	35/0	36/0
	37/0	38/0	39/0	40/0	41/5				
Control sub system	42/2	43/1	44/4	45/0	46/3	47/3			
Environmental...	48/0	49/0	50/0	51/2	52/0	53/0	54/0	55/0	
System Economics	56/4	57/3	58/1	59/0	60/0	61/3	62/0		
Physical	63/0	64/2	65/0	66/0	67/0	68/3	69/2	70/3	71/2
Compressor Attributes	72/S	73/0	74/0	75/0	76/0	77/0			
Condenser Attributes	78/WC	79/0	80/0	81/0	82/0	83/0	84/0	85/0	
	86/0	87/0	88/0	89/0	90/0	91/0	92/0		
Chiller Attributes	93/F	94/0	95/0	96/0	97/0	98/0	99/0	100/0	
	101/0	102/0	103/0	104/0	105/0	106/0	107/0		
Pump Attributes	108/C	109/0	110/0	111/0	112/0	113/0	114/0	115/0	
Cooling & Feed water	116/1	117/0	118/0	119/0	120/0	121/0	122/0	123/0	
Heating Equipment	124/0	125/0	126/0	127/0	128/0	129/0	130/0	131/0	
	132/0	133/0	134/0	135/0					
Air Handling & Distribution	136/H	137/0	138/0	139/0	140/0	141/0	142/0	143/0	
	144/4	145/0	146/0	147/0	148/0	149/0	150/0	151/0	
	152/0	153/0	154/0	155/0	156/0	157/0			
Pipe Attributes	158/0	159/0	160/0	161/0	162/0				
Cooling Tower	163/ID	164/3	165/3	166/0	167/0	168/0	169/3	170/0	
	171/0	172/0	173/0						

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### **3.4 The 3 – Stage Selection Procedure**

#### **3.4.1. Elimination Search (Stage 1)**

All the 173 attributes which we have been identified in the previous section would not be important in selection of air conditioning system for particular application. There will be a small number of attributes which may be set aside as pertinent attributes which will have direct effect on the selection procedure. The threshold values to these pertinent attributes can be assigned by obtaining information from the user and group of experts. Hence forth this work will focus solely on the pertinent attributes, leaving out the rest. On the basis of threshold values of these pertinent attributes, a large list of available air conditioning system alternatives can be converged to a shortlist. To achieve this, the database is scanned for the pertinent attributes, one at a time, and the air conditioning system attributes with one or more pertinent attributes falling short of the minimum required (threshold) values for selection are eliminated. This saves computational time by narrow down the selection process considerably.

#### **3.4.2 TOPSIS Approach (Stage 2)**

##### **3.4.2.1. Evaluation Procedure**

A shortlist of air conditioning system alternatives formed as a result of ‘elimination search’ have to be further filtered to find out the best solution out of all i.e. an optimal air conditioning system. Hence these available alternatives are ranked in order of preference to select an optimal one.

##### **3.4.2.2. Decision Matrix**

Firstly all of the information available from the mini database about these satisfying solutions is represented in the matrix form. Such a matrix is termed as decision matrix, ‘**D**’. Each row of the matrix is allocated to one alternative air conditioning system and each column to one attribute. Therefore an element  $d_{ij}$  of the decision matrix, ‘**D**’ represents the value of  $j^{\text{th}}$  attribute in non-normalized form/units, corresponding to  $i^{\text{th}}$  alternative. Thus if there are ‘ $m$ ’ short-listed alternatives with ‘ $n$ ’ pertinent attributes, the decision matrix is an  $m \times n$  matrix.

### 3.4.2.3. Normalized Matrix

As the elements in each column of matrix, ‘**D**’ have different units and scales, it is necessary to normalize their values. Thus normalized matrix, ‘**N**’ is constructed to have the dimensionless magnitudes of all the attributes of air conditioning system on common scale of 0 to 1, which allows the comparison across the attributes. Each element  $n_{ij}$  of the normalized matrix, ‘**N**’ can be calculated as

$$n_{ij} = \frac{d_{ij}}{\sqrt{\sum_{i=1}^m d_{ij}^2}} \quad (1)$$

where  $d_{ij}$  is an element of the decision matrix, ‘**D**’.

### 3.4.2.4. Relative Importance Matrix

In this step, the relative importance matrix ‘**R**’ of size  $n \times n$  is formed to incorporate the relative importance of the attributes over other for a given application. An element  $r_{ij}$  of matrix ‘**R**’ represents the relative importance of the  $i^{\text{th}}$  attribute over the  $j^{\text{th}}$  attribute and is defined as

$$r_{ij} = \frac{\text{importance of } i^{\text{th}} \text{ attribute}}{\text{importance of } j^{\text{th}} \text{ attribute}} \quad (2)$$

The relative importance of one attribute with respect to another for a given application can be obtained from the user or the group of experts specialized in a particular application. The information about the pair-wise comparison of attributes for a particular application is stored in this relative importance matrix ‘**R**’, with all its diagonal elements as unity.

### 3.4.2.5. Eigen Value Formulation and Weight Matrix

Due to human inconsistencies, the information stored in the ‘**R**’ matrix on a pair-wise basis cannot be used directly. It must be modified into a form that gives the relative weights of all attributes taken together so that the sum of all the weight is equal to unity. Thus eigen value formulation is used to find weight vector matrix, ‘**W**’ and is expressed as

$$RW = \lambda W \quad (3)$$

where  $W = \{w_1, w_2, w_3, \dots, w_n\}^T$ , and  $\lambda$  is the eigen value.

Eq. (3) can be expressed as

$$(R - \lambda I)W = 0 \quad (4)$$

To avoid the trivial solution, we have

$$\det(R - \lambda I) = 0 \quad (5)$$

The solution of Eq. (5) gives the set of 'n' eigen values ( $\lambda_1, \lambda_2, \dots, \lambda_n$ ). The solution of Eq. (4) for the maximum eigen value ' $\lambda_{\max}$ ' gives the weight matrix, ' $\mathbf{W}$ ' and the expression is given as

$$(R - \lambda_{\max} I)W = 0 \quad (6)$$

### 3.4.2.6. Weighted Normalized Decision Matrix

In this step the weighted normalized decision matrix, ' $\mathbf{V}$ ' is obtained by incorporating the information stored in the weight matrix, ' $\mathbf{W}$ ' into the normalized matrix, ' $\mathbf{N}$ '. A true comparable value of each attribute is given by this weighted normalized matrix and is defined as

$$V = [v_{ij}], \text{ where } v_{ij} = w_j \times n_{ij}, \quad (7)$$

where  $i = 1, 2, \dots, m; j = 1, 2, \dots, n$

### 3.4.2.7. Hypothetical Best and Worst Solution

The hypothetical best solution (HBS) and hypothetical worst solution (HWS) are determined by choosing the maximum and minimum values of attributes from ' $\mathbf{V}$ ' matrix as

$$\begin{aligned} \text{HBS} = A^* &= v_{ij \max}, \text{ for benefit attributes} \\ &\quad \text{(larger the better type), or} \\ &= v_{ij \min}, \text{ for cost attributes} \\ &\quad \text{(smaller the better type), and} \end{aligned} \quad (8)$$

$$\begin{aligned} \text{HWS} = A^- &= v_{ij \min}, \text{ for benefit attributes} \\ &\quad \text{(larger the better type), or} \\ &= v_{ij \max}, \text{ for cost attributes} \\ &\quad \text{(smaller the better type)} \end{aligned} \quad (9)$$

Where  $i = 1, 2, \dots, m$  and  $j = 1, 2, \dots, n$ . Hence,

$$A^* = (V^*_1, V^*_2, \dots, V^*_n)$$

$$A^- = (V^-_1, V^-_2, \dots, V^-_n)$$

### 3.4.2.8. Determination of Separation Measures

The TOPSIS procedure is based on the concept that the chosen option should be nearest to the HBS and farthest from the HWS. The separation measure of top ranked air conditioning

system ensures that it is closest to the HBS (best possible air conditioning system) and farthest from the HWS (worst possible air conditioning system). If  $S_i^*$  and  $S_i^-$  are separation measures from HBS and HWS, respectively. Then, the separation of each alternative from the HBS is given by

$$S_i^* = [\sum_{j=1}^n (v_{ij} - v_j^*)^2]^{1/2} \quad (i = 1, 2, 3, \dots, m) \quad (10)$$

And separation measure from HWS is given by

$$S_i^- = [\sum_{j=1}^n (v_{ij} - v_j^-)^2]^{1/2} \quad (i = 1, 2, 3, \dots, m) \quad (11)$$

#### 3.4.2.9. Determination of Suitability Index

The suitability index, 'C\*' is a measure of the suitability of the air conditioning system for the chosen application on the basis of attributes considered. It is defined as the relative closeness to the HBS, and is expressed as

$$C^* = S_i^- / (S_i^* + S_i^-), \quad i = 1, 2, \dots, m \quad (12)$$

An air conditioning system with largest C\* is preferable.

#### 3.4.2.10. Establishing an Order of Preference

The air conditioning system with highest value of C\* will be given highest rank, and so on. In this way the preference order for the available alternative air conditioning systems is obtained by arranging them in decreasing order of their corresponding C\* values.

### 3.4.3 Final Selection of the Best/Optimal System (Stage 3)

The final selection of an optimal air conditioning system for a given application after preparing a preference order can be done on the basis of several other factors which were not previously considered in coding and evaluation, such as economic considerations, environmental aspects, availability, operational simplicity, international market policies, etc. Some factors can support the decision and some can oppose the decision. So, to assist the user/top management in final selection, a powerful decision making tool namely 'force field analysis' is suggested. It is a useful technique for looking at all the forces/factors for and against a decision. By recognizing that every decision has forces that support the decision and forces that oppose the decision, users/managers can make smarter decisions. By evaluating these forces, decision-maker can know the likelihood of acceptance of decision. To carry out a force field analysis, following steps should be followed:

1. Brainstorm the forces for and against a decision and list them in two different columns respectively. Include intangible or emotional factors, as ignoring these can make the decision less effective.
2. Assign a score to each force, from 1 (low or weak) to 5 (high or strong). Draw opposing arrows for each factor and show the size of each force as a number next to it.
3. Total the For and Against scores and determine whether your heart and head agree for the result because it may be possible to increase the For score and decrease the Against score by taking appropriate action.
4. If not satisfied, review the factors and decide what actions could be taken to address or enhance any challenges and imply the action strategy.
5. Total the For and Against new scores and get a crystal clear decision which is sound, transparent and explainable.

Hence decision maker can decide whether to select the top ranked alternative or to go for next choice from the available alternatives.

### **3.5 Illustrative Example**

The multiple attribute decision making (MADM) method is applied to solve the problem of evaluation and selection of air conditioning system. The step-by- step procedure discussed in the earlier section is applied as follows.

The proposed methodology is applied for the evaluation and selection of an air conditioning system for an office, with inside design conditions 24°C, 50±10% RH and outdoor design temperature 45°C. The architecture structure and dimensions of an office are described as follows:

The total floor area of an office to be air conditioned is 2000 ft<sup>2</sup> with wall thickness of 12 inches. The office is located on the ground floor of the three storey building, with no basement. The two floors of the building which are above the office are non AC. Also the building sharing the west wall of an office is non AC. Inside an office, along with 1 watt/ft<sup>2</sup> of lighting load, there are ten numbers of computers and one coffee machine. The occupancy of an office is 50 people and fresh air change is equal to one cycle per hour. Via calculation, the design space cooling load is estimated as 16.5 TR. According to the building location, climate and other conditions, a large database of air conditioning system alternatives for 16.5TR capacity is generated.

### 3.5.1 Stage 1

The critical attributes i.e. minimum requirement, for elimination search is as follows:

1. Type of system (basic working cycle) = Vapour compression system
2. Cooling capacity = 16.5 TR
3. Power consumption = maximum 1.5 KW/ton/hr
4. Type of refrigerant = Eco-friendly refrigerant
5. Air through = at least 12 ft
6. Equipment cost = More, above average, average, below average, less
7. Aesthetics = average
8. Useful life = at least 10 years

From the database generated, after applying the elimination search for threshold values of the attributes as given in the problem statement, we are left with a manageable number of alternatives and their pertinent attributes. They are listed in Table 3.4. There are more attributes which can also be considered, but these are sufficient to illustrate the methodology.

Table 3.4 Attributes for the candidate air conditioning systems

	Noise level	Equipment cost	Energy consumption (KW/ton/hr)	Air through (Ft)	Ease of service and maintenance
Split AC (8 Nos)	4	2	1.35	12	2
Ductable Split AC	3	3	1.24	25	4
Packaged air cooled AC	2	4	1.1	25	5
Packaged water cooled AC	2	5	1	25	3

Here, some of the attributes such as noise level, equipment cost, and ease of service and maintenance are subjective in nature, so they are graded on a relative scale of 0-5.

The selection procedure for air conditioning system is as follows:

### 3.5.2. Stage 2 – Decision Matrix

Formation of the decision matrix ‘D’, in which the rows of the matrix are candidate air conditioning systems and the columns are their attribute values.

$$D = \begin{bmatrix} 4 & 2 & 1.35 & 12 & 2 \\ 3 & 3 & 1.24 & 25 & 4 \\ 2 & 4 & 1.1 & 25 & 5 \\ 2 & 5 & 1 & 25 & 3 \end{bmatrix}$$

### 3.5.3 Normalized Matrix

Calculation of each element of the normalized matrix, 'N' using Eq. (1)

$$N = \begin{bmatrix} 0.6963 & 0.2722 & 0.5720 & 0.2671 & 0.2722 \\ 0.5222 & 0.4082 & 0.5254 & 0.5564 & 0.5443 \\ 0.3481 & 0.5443 & 0.4661 & 0.5564 & 0.6804 \\ 0.3481 & 0.6804 & 0.4237 & 0.5564 & 0.4082 \end{bmatrix}$$

### 3.5.4 Relative Importance Matrix

A group of experts and the user will decide the relative importance of one attributes with respect to each other for a given application as per Eq. (2). The symmetric terms are taken reciprocals of each other and the matrix, 'R' may be written down as

$$R = \begin{bmatrix} 1 & 1 & 2 & 0.5 & 0.33 \\ 1 & 1 & 0.5 & 2 & 2 \\ 0.5 & 2 & 1 & 3 & 2 \\ 2 & 0.5 & 0.33 & 1 & 0.33 \\ 3 & 0.5 & 0.5 & 3 & 1 \end{bmatrix}$$

### 3.5.5. Weight Vector

Using Eq. (4) and Eq. (5), Maximum eigen value of the relative importance matrix R is obtained as follow:

$$(R - \lambda I) = \begin{bmatrix} 1-\lambda & 1 & 2 & 0.5 & 0.33 \\ 1 & 1-\lambda & 0.5 & 2 & 2 \\ 0.5 & 2 & 1-\lambda & 3 & 2 \\ 2 & 0.5 & 0.33 & 1-\lambda & 0.33 \\ 3 & 0.5 & 0.5 & 3 & 1-\lambda \end{bmatrix}$$

$$\det(\mathbf{R} - \lambda \mathbf{I}) = 0$$

We get,  $\lambda_{max} = 6$

$$(\mathbf{R} - \lambda_{max}\mathbf{I}) = \begin{bmatrix} -5 & 1 & 2 & 0.5 & 0.33 \\ 1 & -5 & 0.5 & 2 & 2 \\ 0.5 & 2 & -5 & 3 & 2 \\ 2 & 0.5 & 0.33 & -5 & 0.33 \\ 3 & 0.5 & 0.5 & 3 & -5 \end{bmatrix}$$

Using Eq. (6), weights for each attribute are obtained using eigen vector associated with maximum eigen value and this weight vector is given as

$$(\mathbf{R} - \lambda_{max}\mathbf{I})\mathbf{w} = 0$$

$$\begin{bmatrix} -5 & 1 & 2 & 0.5 & 0.33 \\ 1 & -5 & 0.5 & 2 & 2 \\ 0.5 & 2 & -5 & 3 & 2 \\ 2 & 0.5 & 0.33 & -5 & 0.33 \\ 3 & 0.5 & 0.5 & 3 & -5 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \\ w_5 \end{bmatrix} = 0$$

$$w_1 + w_2 + w_3 + w_4 + w_5 = 1$$

$$\mathbf{W} = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \\ w_5 \end{bmatrix} = \begin{bmatrix} 0.1761 \\ 0.2042 \\ 0.2668 \\ 0.1243 \\ 0.2286 \end{bmatrix}$$

### 3.5.6 Weighted Normalized Decision Matrix

Weighted normalized decision matrix, ' $\mathbf{V}$ ' is obtained by substituting the values of ' $\mathbf{R}$ ' and ' $\mathbf{W}$ ' in Eq. (7) and is written as

$$V = \begin{bmatrix} 0.1226 & 0.0556 & 0.1526 & 0.0332 & 0.0622 \\ 0.0920 & 0.0833 & 0.1402 & 0.0692 & 0.1244 \\ 0.0613 & 0.1111 & 0.1243 & 0.0692 & 0.1555 \\ 0.0613 & 0.1389 & 0.1130 & 0.0692 & 0.0933 \end{bmatrix}$$

### 3.5.7 Hypothetical Best and Worst Solution

Hypothetical best and worst solution for each attribute after following the expressions (8) and (9) are obtained which are as follows:

$$V^* = (0.0613 \quad 0.0556 \quad 0.1130 \quad 0.0692 \quad 0.1555)$$

$$V^- = (0.1226 \quad 0.1389 \quad 0.1526 \quad 0.0332 \quad 0.0622)$$

### 3.5.8 Determination of Separation Measures

Based on the method described in expressions (10) and (11) the separation measures  $S_i^*$  and  $S_i^-$  for the four air conditioning system alternatives are calculated and the values for the same are as follows:

$$S_1^* = 0.1238 \quad S_1^- = 0.0833$$

$$S_2^* = 0.0584 \quad S_2^- = 0.0966$$

$$S_3^* = 0.0566 \quad S_3^- = 0.1238$$

$$S_4^* = 0.1039 \quad S_4^- = 0.0871$$

### 3.5.9. Determination of Suitability Index

The relative closeness to ideal solution or the suitability index is obtained based on the expression (12) discussed earlier and the indices for all the four alternatives are given as under:

$$C_1^* = 0.4022$$

$$C_2^* = 0.6232$$

$$C_3^* = 0.6862$$

$$C_4^* = 0.4560$$

### 3.5.10. Establishing a Order of Preference

The preference order for the available alternative air conditioning systems is obtained by arranging them in decreasing order of their corresponding  $C^*$  values. The first rank is allotted to the alternative with highest value of  $C^*$  and the last rank is given to the lowest value of  $C^*$ . Ranking of all the four alternatives is also obtained through graphical methods such as line graph and spider diagram. The comparison of ranking is shown in Table 3.4.

Table 3.5

Evaluation and ranking of four alternative air conditioning systems

	TOPSIS Suitability Index	Rank
Packaged air cooled AC	0.6862	1
Ductable Split AC	0.6232	2
Packaged water cooled AC	0.4560	3
Split AC (8 Nos.)	0.4022	4

### 3.5.11. Stage 3 - Final Selection

The last step in this methodology is the final selection of an optimal air conditioning system for this given application. As mentioned earlier, this final selection, after preparing a preference order, can be done by using powerful decision making tool namely 'force field analysis'. In order to explain this tool, attempt is made to carry out the force field analysis of a decision to select the packaged air cooled AC (rank 1) for the application as given in example and is shown in Figure 3.1. The procedure to conduct force field analysis is discussed in previous section. Since total of 'For score' is greater than as that of 'Against score', packaged air cooled AC will be the optimal air conditioning system for the application given in example.

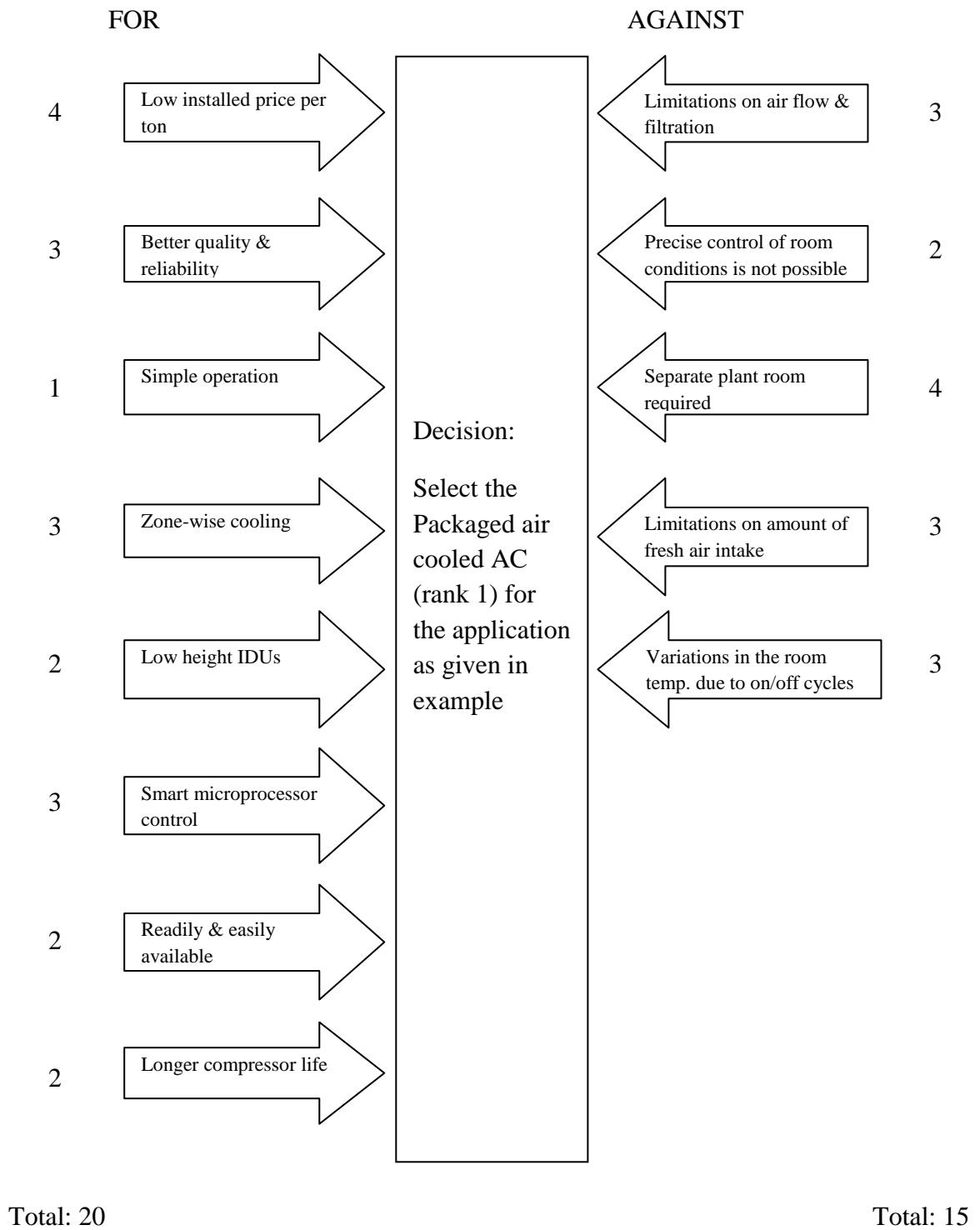


Figure 3.1 Force Field analysis

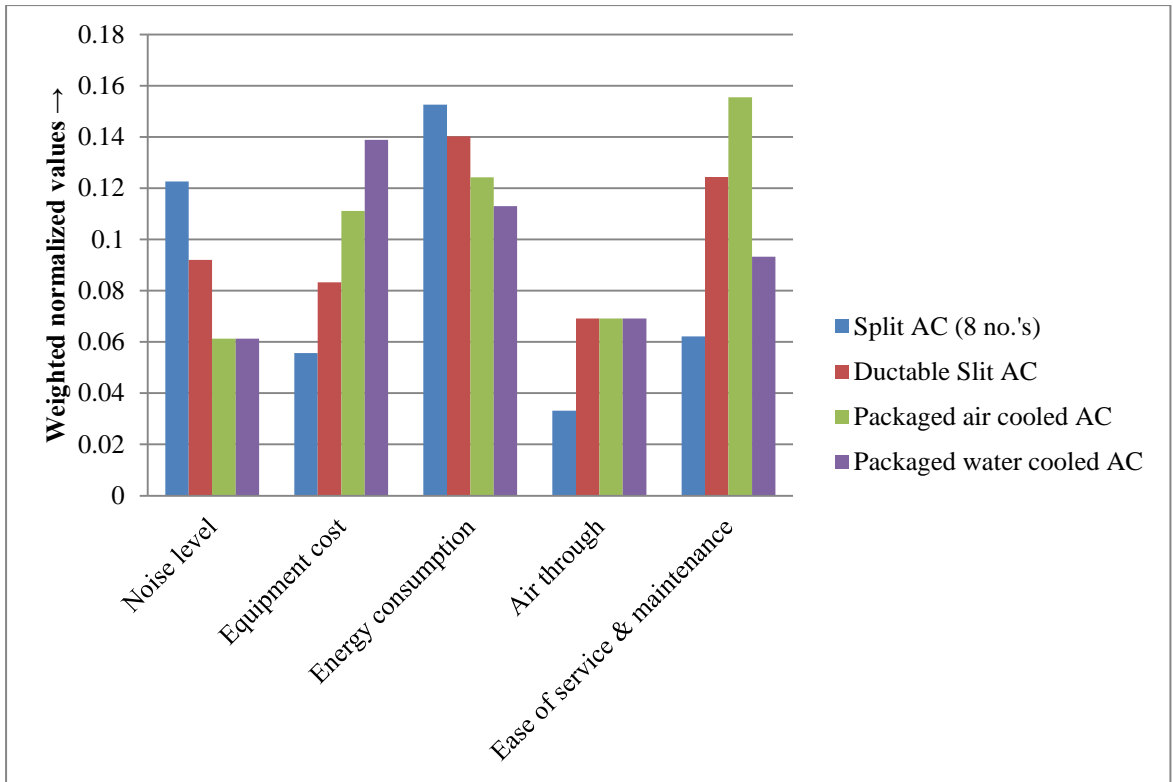


Figure 3.2(a)

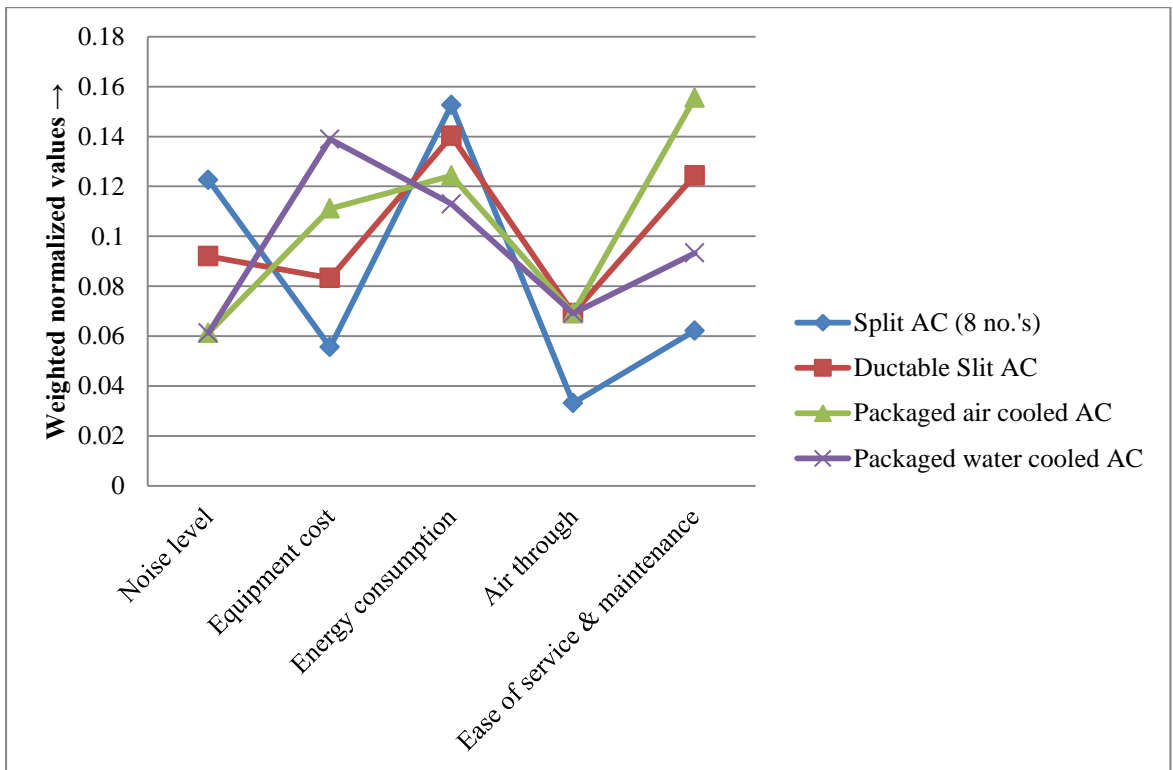


Figure 3.2 (b)

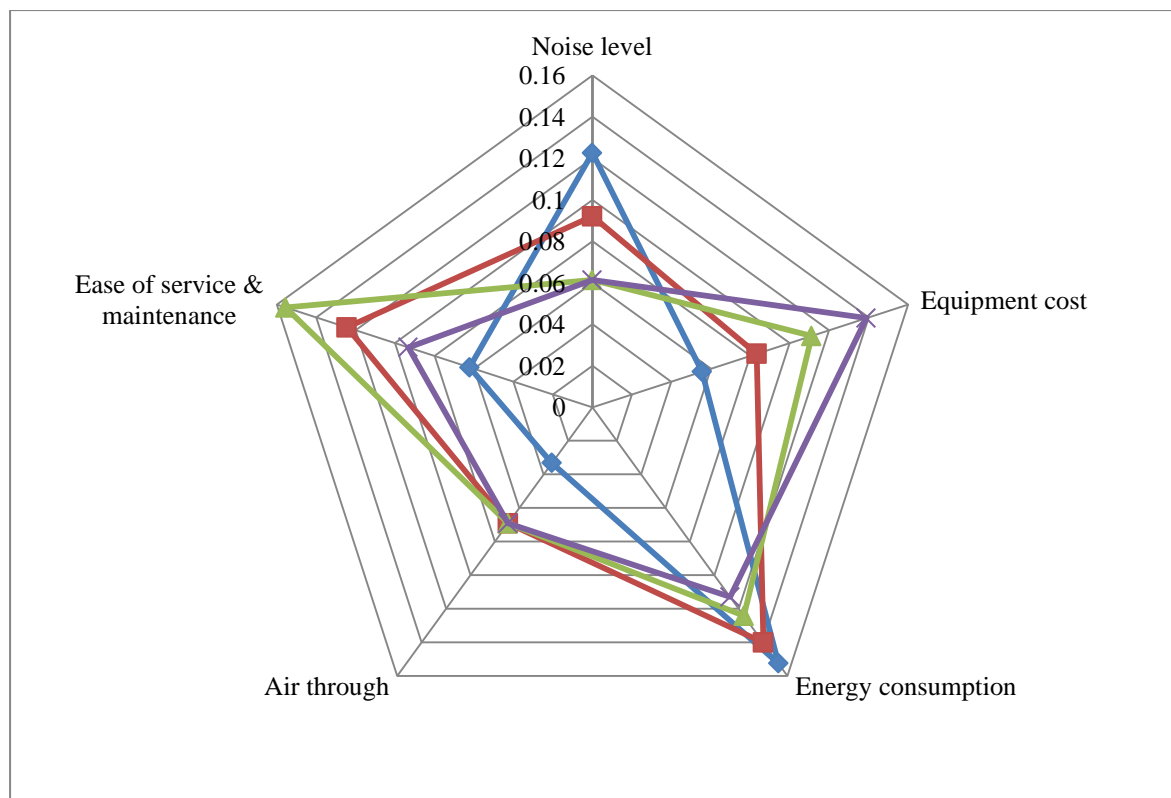


Figure 3.2(c)

Fig.3 2. Comparative Profile Diagrams of Air Conditioning Systems Using (a) HCT, (b) GCT, and (c) RCT

### 3.6 Graphical Comparison Techniques

Till now TOPSIS based evaluation of an air conditioning system has been discussed. This approach is mathematical in nature. Merely mathematical figures are not enough for the top management to take the decision for the final approval. So, to minimize the complexity of mathematics and to enhance the insight and better understanding of the available alternatives, three graphical techniques namely histogram, graphical and radar are suggested for use. These methods give a complete picture of a short-listed alternative and make the choice/comparison more effective.

From the weighted normalized matrix, containing the information of various pertinent attributes of various air conditioning system alternatives, histograms (HCT) and graphs (GCT) are constructed for each of the short-listed air conditioning system alternatives by plotting the magnitude of each attribute on the vertical axis and the attributes on the horizontal axis. These graphs give the attribute comparison for the short-listed air conditioning system alternatives. If  $n$  be the number of attributes under consideration, radar diagrams

(RCT) are formed by constructing the radial lines spaced at  $360^\circ/n$  apart in the clockwise or anti-clockwise direction. Each line can be used to represent an attribute for the selected air conditioning system, on which points corresponding to weighted normalized values for that attribute are marked. These attribute profiles obtained for various alternative air conditioning systems are superimposed to make comparative profile diagrams and are shown in Figure 3.2.

### **3.7 Usefulness of the proposed methodology**

#### **3.7.1 Usefulness to the Designer**

1. The proposed methodology is useful for design engineer at conceptual stage because it will help him to generate various alternative designs keeping in mind the critical attributes which directly affect the performance.
2. With the help of this methodology, the designer can obtain the required performance of air conditioning system by changing the critical attributes and obtaining the relevant results.
3. The designer can use the attributes for cause and effect analysis, which can help him in identifying the effects of manipulating these attributes on the air conditioning system performance.

#### **3.7.2 Usefulness to the Manufacturer**

1. The manufacturer, with the help of quantification of relevant attributes, can understand these attributes and fulfil the demand of the user precisely.
2. The manufacturer can find out the market trend by observing the magnitude of the attributes and can also modify his product to suit the needs of the user.
3. The proposed methodology will help the manufacturer in production of optimum air conditioning system in minimum possible time and cost.
4. The generated hypothetically best air conditioning system is useful for industries in setting up the benchmark air conditioning system.
5. The air conditioning system manufacturer can use the attributes to carry out Strength-Weakness-Opportunities-Threats (SWOT) analysis of his product.

### **3.7.3 Usefulness to the User**

1. The proposed methodology will help in generation of a large database of available air conditioning systems and their subsequent retrieval which will help the user to select the optimal air conditioning system for the particular application.
2. This methodology will provide a good technical knowledge to the user, about the product which he will purchase.

### **3.7.4 Usefulness to the Maintenance Personnel**

1. The proposed methodology will help the maintenance personnel by providing a database which is beneficial for him during maintenance stages because it provides knowledge about the various sub-components of the air conditioning system.
2. The maintenance personnel can plan maintenance strategy to reduce the down time.

### **3.8 Step-by-step procedure for the industry**

1. Decide about the short term and long term strategy to develop a series of air conditioning systems.
2. Carry out cause and effect analysis to identify all the relevant attributes and prepare the list of attributes.
3. Carry out SWOT analysis to decide the attribute based specification.
4. Using Morphological chart procedure to identify different design solutions (alternatives).
5. Carry out Elimination search based on pertinent attributes to reduce long list into manageable list of alternatives satisfying all the requirements.
6. Attribute based evaluation using TOPSIS is carried out for all the feasible solutions using MADM-TOPSIS approach.
7. Rank all these feasible solutions in order of preference based on the procedure proposed.
8. SWOT Analysis or Force Field Analysis is needed to take final decisions considering different constraints and existing strength, weakness, opportunities and threats, short term and long term management strategy.

This work presents a methodology useful for optimum selection of an air conditioning system based on Multiple Attribute Decision Making (MADM) approach. A methodology based on

Multiple Attribute Decision Making (MADM) approach is proposed and is useful for evaluation, comparison, ranking and optimum selection of air conditioning system or subsystem for particular application. A 3-stage selection procedure including elimination search, TOPSIS approach and other graphical methods (line graph and spider diagram) on the basis of identified pertinent attributes and the separation of each alternative from generated hypothetically best and worst air conditioning systems, helps in ranking of all the air conditioning system alternatives. It is recommended that the information about all the attributes related to an air conditioning system should be maintained as knowledge base for future usage by the manufacturer. This information will be helpful to himself apart from air conditioning system designer, maintenance personnel, user, etc. The proposed method is suitable for the manufacturer to develop electronic database of air conditioning systems available in the global market and develop specifications for future systems.

# STRUCTURAL MODELING AND ANALYSIS OF AIR CONDITIONING SYSTEM

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### 4.1 Need for Structural Modeling and Analysis of Air Conditioning System

In general, the air conditioning systems are mechanical systems providing artificial environment for either operational requirement, or health and comfort of the occupants. An air conditioning system consists of a number of components. These components are having different functionalities and are from different disciplinary backgrounds like mechanical, electrical, electronics, IT etc. or combination of these. In physical systems, interactions exist among these components. The components are connected in certain configurations that allow thermal energy to be transported and air to be conditioned and distributed. Over the last century, many types of air conditioning systems and system configuration have been developed. The topology of how the components are connected effects the performance of the configuration. A system performance is the combined effect of its constituents and the interactions between these constituents [40]. Each component in the configuration is dedicated to perform certain function of air-conditioning. The behaviour of each of the components is controlled by a number of parameters associated to it. Therefore, the integration and compatibility among the components also affects the functionality, quality, performance, etc. of an air conditioning system. Many authors have converged towards a particular subsystem oriented design, for example air-flow control sub system oriented air conditioning system design [23]. Design of an air conditioning system considering all these interactions, is a complex job.

From the literature review given in chapter 2, we can say that no one has considered the structural constituents for analyzing air conditioning system along with their interactions at the conceptual and design stages, and also there is no methodology proposed for an integrated system approach for analyzing air conditioning systems, i.e., by considering the subsystems as its constituents, and their interactions, interdependence, and connectivities. There is a need to develop a mathematical model that can help in analysis and synthesis of an air conditioning system at conceptual stage and also in developing a virtual model.

Also in literature review there is good number of applications of system models using graph theory for the structural modeling and analysis of different engineering systems [40-43]. Thus, for the modeling and analysis of the air conditioning system, it is quite logical to select the graph theory and matrix algebra.

## **4.2 Introduction to Graph Theoretic Approach**

To fill the research gap and to unveil the importance of a structure based air conditioning system design, a graph theory based air conditioning system model is proposed. The model can include all the subsystems along with the interactions therein and thus becomes a tool for total air conditioning system analysis. A graph is useful for visual analysis of an air conditioning system, but quantification of these interactions is necessary for design and analysis. Matrix algebra is used for quantifying these interactions.

A graph  $G = (V, E)$  [1] consists of a set of objects  $V = \{v_1, v_2, \dots\}$  called vertices or nodes, and another set  $E = \{e_1, e_2, \dots\}$ , of which the elements are called edges, such that each edge  $e_k$  is identified with a pair of vertices. The vertices  $v_i$  and  $v_j$  associated with edge  $e_k$  are called the end vertices of  $e_k$ . The most common representation of a graph is by means of a diagram, in which the vertices are represented by small points or circles, and each edge as a line segment joining its end vertices. The application of graph theory was known centuries ago, when the longstanding problem of the Konigsberg bridge was solved by Leonhard Euler in 1736 by means of a graph. Since then, the graph theory has been applied in various fields of engineering such as physics, chemistry, mathematics, electrical engineering, sociology, computer technology (net working), economics, operation research, linguistics etc. Graph theory has served an important purpose in the modeling of systems, network analysis, functional representation, conceptual modeling, diagnosis, etc. The graphs are used to represent almost any physical situation involving discrete objects and relationship among them. It is found only in recent researches that the graph theoretic techniques are being applied for the characterization and identification of chemical compounds. Graphs have been used in linguistics to depict parsing diagrams. Digraphs under the name sociograms have been used to represent relationship among individuals in a society (or group). Graph theory is not only effective in dealing with the structure of the system, or implicitly, but also useful in handling problems of structural relationship. Graph theory [44], which consider sub-systems and interactions has been extensively applied in various areas such as, structural modeling and analysis of composite product system [41], structural modeling and integrative analysis

of manufacturing systems [42], structural modeling and analysis of a mechatronic system [43], structural analysis of automobile vehicle [45], structural classification of kinematic chains and mechanisms [46], etc.

This chapter presents the details of graph theory and the matrix approach for structural modeling and analysis of an air conditioning system.

### **4.3 Identification of Structural Constituents of the Air Conditioning System and their Interactions**

A normal air conditioning system consists of a large number of components. These components are having different functionalities and are from different disciplinary backgrounds like mechanical, electrical, electronics, etc. or combination of these. In physical systems interactions exist among these components. In normal room air conditioning system, indoor cooling is achieved using a refrigeration loop comprised of five main components: compressor, condenser, evaporator, expansion valve, and drier. The compressor receives low pressure refrigerant gas and delivers high pressure gas to the condenser (also a heat exchanger), where it condenses, and dissipating energy to the outside air. The high pressure liquid then flows to the evaporator through an expansion valve, which maintains the pressure difference in the loop. As the refrigerant expands, heat energy is absorbed through the evaporator, which is another heat exchanger over which warm indoor room air is passed. The drier is located in the high pressure section of the system, usually in the plumbing between condenser outlet and the expansion valve inlet. The function of the drier is to absorb moisture that may have gotten inside the air conditioning system during manufacture, assembly, or service. The condenser fan and evaporator blower assist the condenser and evaporator respectively in heat transfer process. A attempt is made to identify the different structural constituents of air conditioning system contributing the system performance and arrange them into five subgroups as shown in Table 4.1

Table 4.1 Structural constituents of an air conditioning system.

<b>Component</b>	<b>Function</b>
Compressor ( $S_1$ )	The compressor transfers energy, in form of increased pressure, to the refrigerant before it is passed to the condenser.

Heat Rejection system (S <sub>2</sub> )	The condenser, with the help of condenser fan, dissipates refrigerant system heat energy, via forced convection, to the outside surroundings in order to cool/liquefy the refrigerant. The condenser fan draws outside air and provides airflow across the condenser.
Control System (S <sub>3</sub> )	The control system provides temperature control, humidifying/dehumidifying controls, air flow controls, safety controls, etc.
Expansion valve (S <sub>4</sub> )	The expansion valve accepts refrigerant from the condenser via drier and maintains the pressure difference in the loop by reducing the pressure levels within the system and it also controls the amount of refrigerant flow into the evaporator.
Heat Absorption System (S <sub>5</sub> )	It contains the evaporator core which absorbs heat energy, via forced convection, from the room indoor air (to the refrigerant) to provide cooled air for the room interior and the blower which provides the circulation of indoor air to the evaporator core.

The performance of an air conditioning system depends on individual performance of subsystems and sub-subsystems along with interactions/interdependences/influences between them. Identification of different types of interactions and their modeling quantification is very critical. Consideration of only right sub systems up to component and interactions amongst them may be different for different air conditioning industries based on the type of air conditioning system. The structural constituents/components are interrelated and interdependent on each other in many ways and such interactions come about due to a number of effects, including energy and material transfers, among others. Example of an air conditioning system interaction is the transfer of refrigerant and energy via the refrigerant between the compressor and Heat rejection system. So there is material (refrigerant) as well as energy (heat energy) transfer between compressor and heat rejection system. Similarly, there is an information flow from control system to the compressor because after taking input of evaporator temperature from the evaporator core, the control system provides information to the compressor in order to turn it on or off. In the same sense, all the five identified subsystems of an air conditioning are interrelated with each other.

So, by considering taxonomy of interactions and with the help of air conditioning system engineers and domain experts, components interaction information is identified. Also engineering models and hardware provided the useful insight into component-level interactions.

In the present work, four generic interaction types are considered as follows:

- 1) **Spatial:** A spatial-type interaction identifies needs for adjacency or orientation between two elements. Associations of physical space and alignment.
- 2) **Energy:** An energy-type interaction identifies needs for energy transfer between two elements.
- 3) **Information:** An information-type interaction identifies needs for information or signal exchange between two elements.
- 4) **Material:** A material-type interaction identifies needs for materials exchange between two elements.

The number and definitions of the interaction types is dependent upon the context of the given design problem. In this work, a general case is proposed which is then applied to a problem relatively balanced in the number of interaction types present.

Based on the definition of each of the four interaction types described above, the types needed to capture the essence of the interaction are determined. For example, compressor and heat rejection system are connected to each other through refrigerant pipes and they also exchange refrigerant and energy via the refrigerant. Compressor and Heat absorption system are connected to each other through refrigerant pipes and also refrigerant and energy via refrigerant are transferred from the evaporator core to the compressor. As the drier is assumed under the control system, there is material as well as information exchange between the Heat rejection system and control system. The control system takes information about the evaporator temperature from the heat absorption system and provides information to the compressor and to the evaporator fan i.e. heat absorption system as well as to the condenser fan i.e. heat rejection system. The expansion valve maintains the flow of refrigerant and maintains the pressure different across the system, so there is physical connection as well as material (refrigerant) flow between expansion valve and heat absorption system. Performance of the air conditioning system depends on individual performance of the subsystems along with interactions between them.

The above study shows that to model the structure of the air conditioning system mathematically, it is proposed to identify all these attributes which contribute in the production of final air conditioning system product. An attempt is made to identify all these structural attributes and arrange them under five subsystems as shown in Figure 4.1. This hierarchical tree structure is a generalized one. It is not necessary for every air conditioning system to have all the sub systems as shown in Figure 4.1, there may be some variations for modeling specific air conditioning systems.

Hierarchical tree structure of a system is useful in identifying components at each level and for thorough understanding of physical structure. These subsystems are connected with each other through different interaction types as discussed above. The subsystems and interactions forming an air conditioning system are shown in Figure 4.2.

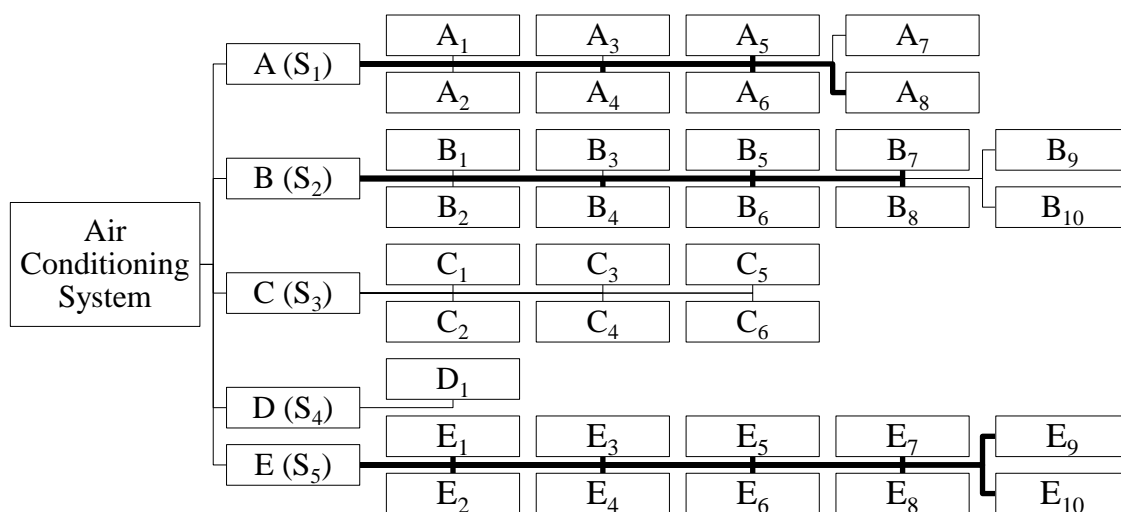


Figure 4.1 Hierarchical classification of the air conditioning system.

A – Compressor, A<sub>1</sub> – Type of compressor, A<sub>2</sub> –Capacity at operating conditions, A<sub>3</sub> – Operating speed, A<sub>4</sub>– Efficiency of compressor, A<sub>5</sub> – BHP/TR at operating speed, A<sub>6</sub> –Type of prime mover, A<sub>7</sub> – Type of refrigerant, A<sub>8</sub> – Noise level

B – Heat rejection system, B<sub>1</sub> – Condenser type, B<sub>2</sub> –Condenser fan type, B<sub>3</sub> – Condenser shell diameter & length, B<sub>4</sub> –Tube material of condenser, B<sub>5</sub> – Fouling factor of condenser,

$B_6$ – No. of tubes of condenser,  $B_7$ – Condenser tube surface area inside/outside,  $B_8$ – Condenser efficiency,  $B_9$ –Refrigerant capacity of condenser,  $B_{10}$ –Maximum cooling capacity of condenser

C – Control system,  $C_1$  – Type of control,  $C_2$  –Degree of automation,  $C_3$  –Control complexity,  $C_4$  – Control flexibility,  $C_5$ – Type of Drier,  $C_6$  –Material of drier,

D – Expansion valve,  $D_1$  –Type of expansion valve

E – Heat absorption system,  $E_1$ – Evaporator type,  $E_2$  – Evaporator fan type,  $E_3$ – Evaporator shell diameter & length,  $E_4$  –Tube material of evaporator,  $E_5$  – Fouling factor of evaporator,  $E_6$ – No. of tubes of evaporator,  $E_7$ – Evaporator tube surface area inside/outside,  $E_8$ – Evaporator efficiency,  $E_9$ –Refrigerant capacity of evaporator,  $E_{10}$ –Maximum cooling capacity of evaporator.

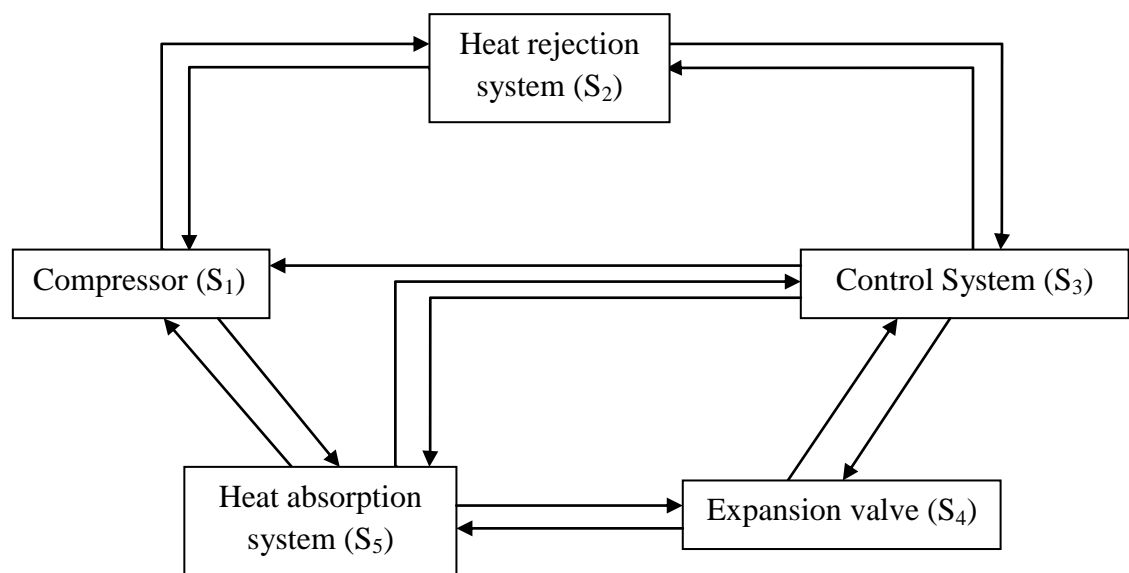


Figure 4.2 Schematic representation of the structure of air conditioning system

#### 4.4 Graph Theoretic Modeling of an Air Conditioning System

Though the schematic diagram of air conditioning system as shown in Figure 4.2 is a good representation of different identified components and their interactions which provides the better understanding of the structure of air conditioning system, but it is not a mathematical entity. To overcome this problem, a graph theory based modeling of an air conditioning system is proposed. A graph theory based mathematical model is derived for representing the physical structure of air conditioning system along with interactions.

All the components of air conditioning system present at level 1, as shown in the Figure 4.1, and interactions among them are represented using a digraph as shown in Figure 4.3. In general graph is represented mathematically by  $G = \{V, E\}$ ; where  $V$  represents nodes/vertices of the graph and  $E$  represents the edges connecting between those nodes [44]. In the case of air conditioning system, let the vertices correspond to subsystems ( $V_i$ ) and the edges ( $e_{ij}$ ) correspond to connectivity/interaction/interdependence of its two sub systems. In Figure 4.3 components of air conditioning system are represented by the vertices of the graph and the interaction of the subsystems are represented by the edges of the graph. Undirected graph are used where directional property is not significant as shown in Figure 4.4. This means that the influence of  $i$ th vertex on  $j$ th vertex is equal to the influence of  $j$ th vertex on  $i$ th vertex. For directed graph i.e. digraph,  $e_{ij} \neq e_{ji}$ .

The air conditioning system graph is a useful mathematical entity and is highly useful for comprehensive understanding of total air conditioning system through for visual analysis. But for computational analysis, the necessary information cannot be sorted in a computer directly. For achieving this objective, the air conditioning system graph can be represented in the form of matrix.

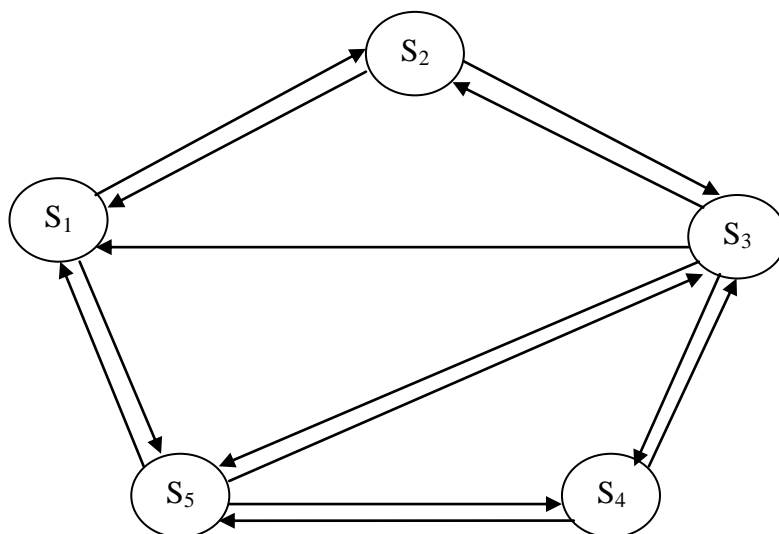


Figure 4.3 Air conditioning system digraph

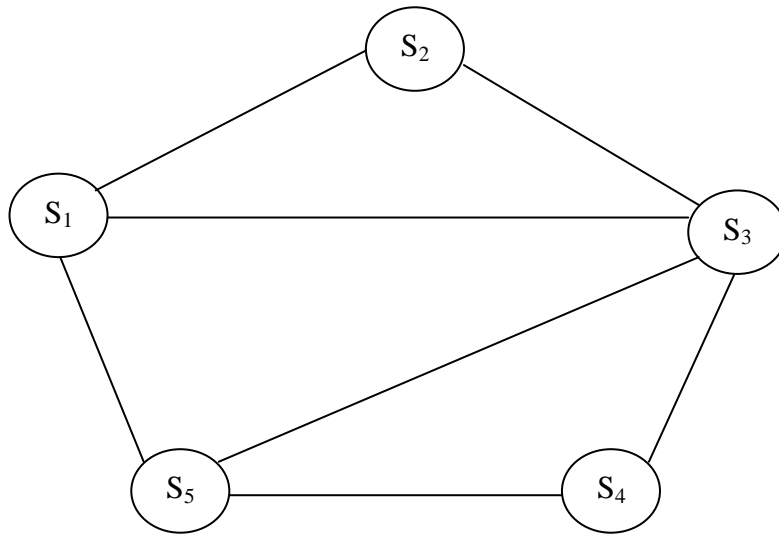


Figure 4.4 Undirected graph representation of the structure of air conditioning system

#### 4.5 Matrix Representation for the Air Conditioning System Graph

To quantify sub systems and interactions in air conditioning system graph an equal mathematical representation known as Matrix is used. The matrix representation permits to carry out storage, retrieval and analysis of air conditioning systems. In general the graph is represented by a matrix called adjacency matrix [44]. Since adjacency matrix represents the physical structure of an air conditioning system, it is termed as System Structure Matrix.

##### 4.5.1 Air Conditioning System Structure Matrix

System structure matrix is a square matrix, having rows and columns correspond to respective sub system. This matrix is a binary square matrix having (0, 1) as elements. Air conditioning system of 'N' sub systems is represented by a structure matrix of size N x N. The system structure matrix of the air conditioning system graph with five nodes will be a five order binary (0,1) square matrix,  $\mathbf{A}=[a_{ij}]$  such that:

$$a_{ij} = \begin{cases} 1, & \text{if subsystem } i \text{ is connected to subsystem } j \\ 0, & \text{if } i \text{ and } j \text{ are not connected} \end{cases}$$

This matrix represents connectivity/interaction between different sub systems of air conditioning system. If the connectivity/interaction exists between two sub systems, it is represented by a binary number '1' and by '0' if there is no connectivity/interaction between

two sub systems. As the subsystem is not interacted with itself therefore  $a_{ii} = 0$ . Although the matrix ‘**A**’ represents the interrelationships/interactions between the different components of the air conditioning system, but it does not represent the characteristics of the air conditioning system.

$$\begin{array}{cccccc}
 & 1 & 2 & 3 & 4 & 5 & \text{subsystems} \\
 \text{A} = & \begin{bmatrix} 0 & 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 1 & 0 \end{bmatrix} & & & & & & (1)
 \end{array}$$

#### 4.5.2 Air Conditioning System Characteristic Matrix

To characterize the air conditioning system, a new matrix **C** is defined using the identity matrix **I**, a variable **S** which represents the air conditioning system, and the adjacency matrix **A**. Based on the standard characteristic equation in mathematics, the air conditioning characteristic matrix **C** for the graph shown in Figure 4.3, may be expressed as [**SI**–**A**].

In Equation (2), the value of all diagonal elements is same (i.e., all air conditioning system components are assumed to be identical which is not true in reality). In real situation different sub systems are having different physical structures and characteristics. Also connectivity represented by a binary number ‘1’ in matrix **C** does not provide information like type of connectivity and degree of interaction. So, Equation (2) is not the complete representation of air conditioning system structure. To overcome this problem, another matrix called the air conditioning system variable characteristic matrix is proposed.

$$\begin{array}{cccccc}
 & 1 & 2 & 3 & 4 & 5 & \text{subsystems} \\
 \text{C} = & \begin{bmatrix} S & -1 & 0 & 0 & -1 \\ -1 & S & -1 & 0 & 0 \\ -1 & -1 & S & -1 & -1 \\ 0 & 0 & -1 & S & -1 \\ -1 & 0 & -1 & -1 & S \end{bmatrix} & & & & & & (2)
 \end{array}$$

#### 4.6.3 Air Conditioning System Variable Characteristic Matrix

The air conditioning system variable characteristic matrix takes into consideration, the effect of different air conditioning subsystem (i.e. components) and their varying degrees of interactions. The air conditioning structure graph in Figure 4.3 is considered for defining this

variable characteristic matrix  $\mathbf{H}$  as below in Equation (3). For this purpose, a five order square matrix  $\mathbf{E}$  with off-diagonal elements  $S_{ij}$  representing varying levels of interactions between the subsystems is defined. Another matrix  $\mathbf{D}$ , a diagonal matrix with diagonal elements  $S_i$ ;  $i=1,2,3,\dots,5$  representing five different subsystems or components is defined. The matrix  $\mathbf{H}$  can be developed from the matrices  $\mathbf{E}$  and  $\mathbf{D}$  as  $\mathbf{H} = [\mathbf{D} - \mathbf{E}]$

$$\begin{array}{cccccc}
 & 1 & 2 & 3 & 4 & 5 & \text{subsystems} \\
 \mathbf{H} = & \left[ \begin{array}{ccccc}
 S_1 & -S_{12} & 0 & 0 & -S_{15} \\
 -S_{21} & S_2 & -S_{23} & 0 & 0 \\
 -S_{31} & -S_{32} & S_3 & -S_{34} & -S_{35} \\
 0 & 0 & -S_{43} & S_4 & -S_{45} \\
 -S_{51} & 0 & -S_{53} & -S_{54} & S_5
 \end{array} \right] & \begin{array}{l} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array}
 \end{array} \quad (3)$$

The above matrix distinctly represents characteristic features of the subsystems and their interactions. Thus, the matrix  $\mathbf{H}$  in Equation (3) is complete structural representation of the air conditioning system capturing all the data related to the air conditioning system including the interactions. This information is useful for analysis, design, and development of new air conditioning systems at conceptual stage or for optimization purposes. The matrix provides a powerful tool through its determinant, called the variable characteristic air conditioning system multinomial. This is a characteristic of the system and represents the complete air conditioning system, considering the effect of air conditioning system components and their interactions.

The determinant of the matrix,  $\mathbf{H}$ , i.e., the variable characteristic air conditioning system multinomial, includes both positive and negative signs. On substituting numerical values in place of diagonal and off-diagonal elements, some of the information is lost in the determinant. This information loss is due to subtraction of some of the terms in the expression. To avoid information loss during mathematical process, another term air conditioning system variable permanent matrix is introduced in the following section.

#### 4.5.4 Air Conditioning System Variable Permanent Matrix

In order to develop a unique and comprehensive model of air conditioning system represented in Figure 4.3, another entity permanent and permanent matrix, frequently used in combinatorial mathematics is proposed. Let the permanent matrix of five-subsystem air conditioning system be defined as

$$\begin{array}{cccccc}
& 1 & 2 & 3 & 4 & 5 & \text{subsystems} \\
\mathbf{F} = & \left[ \begin{array}{ccccc}
S_1 & S_{12} & S_{13} & S_{14} & S_{15} \\
S_{21} & S_2 & S_{23} & S_{24} & S_{25} \\
S_{31} & S_{32} & S_3 & S_{34} & S_{35} \\
S_{41} & S_{42} & S_{43} & S_4 & S_{45} \\
S_{51} & S_{52} & S_{53} & S_{54} & S_5
\end{array} \right] & \begin{array}{l} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array}
\end{array} \quad (4)$$

The Equation (4) is the general expression, in which all the five components of air conditioning system are diagonal elements i.e.  $S_1, S_2, S_3, S_4$  and  $S_5$  and all the off-diagonal elements represents the interactions among these components. This model of expression considers all the quantitative values of the subsystems and interactions, without any loss of information in multinomial representation. Thus, the variable permanent air conditioning system matrix corresponding to the five subsystems as shown in digraph (Figure 4.3) of air conditioning system is given as

$$\begin{array}{cccccc}
& 1 & 2 & 3 & 4 & 5 & \text{subsystems} \\
\mathbf{G} = & \left[ \begin{array}{ccccc}
S_1 & S_{12} & 0 & 0 & S_{15} \\
S_{21} & S_2 & S_{23} & 0 & 0 \\
S_{31} & S_{32} & S_3 & S_{34} & S_{35} \\
0 & 0 & S_{43} & S_4 & S_{45} \\
S_{51} & 0 & S_{53} & S_{54} & S_5
\end{array} \right] & \begin{array}{l} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array}
\end{array} \quad (5)$$

The air conditioning system variable permanent matrix is not a unique representation, by interchanging rows and columns the matrix may change.

#### 4.6 Development of Permanent Function for Air Conditioning System

To develop a unique and comprehensive model of air conditioning system, another entity permanent and permanent matrix, frequently used in combinatorial mathematics [47] is proposed. The permanent function is obtained from a similar manner as its determinant, but all negative terms obtained after expression for the calculation of the determinant of the matrix are replaced with positive equivalent terms. This computation results in a multinomial (Equation (6)) whose every term has a physical significance related to the air conditioning system. The multinomial representation includes all the information regarding various constituents as subsystems and interactions amongst them. The multinomial is derived based on Equation (4), and a numerical index is obtained. When the actual values of each term are

substituted in the multinomial, the final values after the algebraic addition gives a numerical index, which can be considered as a score of total air conditioning system in any performance dimension depending upon the one selected for giving values to the individual structural constituents. This score can prove a powerful tool for comparison, ranking of different air conditioning systems and optimum selection of air conditioning system. Thus permanent function is proposed as a complete tool for the total structural analysis of the air conditioning system. The variable permanent function for an air conditioning system derived from Equation (4) is as follows:

$$\begin{aligned}
\text{Per (F)} = & S_1 S_2 S_3 S_4 S_5 + (S_1 S_2 S_3 S_4^2 S_5 + S_1 S_2 S_4 S_3^2 S_5 + S_1 S_2 S_5 S_3^2 S_4 + S_1 S_3 S_4 S_3^2 S_5 + S_1 S_3 S_5 S_3^2 S_4 \\
& + S_1 S_4 S_5 S_3^2 S_2 + S_2 S_3 S_4 S_3^2 S_5 + S_2 S_3 S_5 S_3^2 S_4 + S_2 S_4 S_5 S_3^2 S_2 + S_3 S_4 S_5 S_3^2 S_2) \\
& + (2S_1 S_2 S_3 S_4 S_5 S_3 + 2S_1 S_3 S_2 S_4 S_5 S_2 + 2S_1 S_4 S_2 S_3 S_5 S_2 + 2S_1 S_5 S_2 S_3 S_4 S_2 \\
& + 2S_3 S_4 S_1 S_2 S_5 S_1 + 2S_3 S_5 S_1 S_2 S_4 S_1 + 2S_2 S_3 S_1 S_4 S_5 S_1 + 2S_2 S_5 S_1 S_3 S_4 S_1 \\
& + 2S_2 S_4 S_1 S_3 S_5 S_1 + 2S_4 S_5 S_1 S_2 S_3 S_1) + (S_1 S_2^2 S_3^2 S_4^2 S_5 + S_1 S_2^2 S_4^2 S_3^2 S_5 + S_1 S_2^2 S_5^2 S_3^2 S_4 \\
& + S_2 S_2^2 S_4^2 S_3^2 S_5 + S_2 S_2^2 S_4^2 S_5^2 S_3 + S_2 S_2^2 S_5^2 S_3^2 S_4 + S_3 S_2^2 S_1 S_2^2 S_4^2 S_5 + S_3 S_2^2 S_1 S_4^2 S_5^2 S_3 \\
& + S_3 S_2^2 S_1 S_5^2 S_3^2 S_4 + S_4 S_2^2 S_1 S_3^2 S_5^2 S_2 + S_4 S_2^2 S_1 S_5^2 S_3^2 S_2 + S_5 S_2^2 S_1 S_3^2 S_4^2 S_2 + S_5 S_2^2 S_1 S_4^2 S_5^2 S_2) \\
& + (2S_1 S_2 S_3 S_3 S_5 S_4 S_2 + 2S_1 S_2 S_3 S_3 S_4 S_5 S_2 + 2S_1 S_2 S_4 S_3 S_3 S_5 S_2 + 2S_2 S_1 S_3 S_3 S_4 S_5 S_1 \\
& + 2S_2 S_1 S_4 S_3 S_3 S_5 S_1 + 2S_2 S_1 S_3 S_3 S_5 S_4 S_1 + 2S_3 S_1 S_2 S_2 S_4 S_5 S_1 + 2S_3 S_1 S_4 S_2 S_2 S_5 S_1 \\
& + 2S_3 S_1 S_2 S_2 S_5 S_4 S_1 + 2S_4 S_1 S_2 S_2 S_3 S_5 S_1 + 2S_4 S_1 S_3 S_2 S_2 S_5 S_1 + 2S_4 S_1 S_2 S_2 S_5 S_3 S_1 \\
& + 2S_5 S_1 S_3 S_2 S_2 S_4 S_1 + 2S_5 S_1 S_2 S_2 S_3 S_4 S_1 + 2S_5 S_1 S_3 S_3 S_4 S_2 S_1) + (2S_1^2 S_2 S_3 S_4 S_5 S_3 \\
& + 2S_1^2 S_3 S_2 S_4 S_5 S_2 + 2S_1^2 S_4 S_2 S_3 S_5 S_2 + 2S_1^2 S_5 S_2 S_3 S_4 S_2 + 2S_2^2 S_3 S_4 S_5 S_1 \\
& + 2S_2^2 S_4 S_1 S_3 S_5 S_1 + 2S_2^2 S_5 S_1 S_3 S_4 S_1 + 2S_2^2 S_3 S_4 S_1 S_2 S_5 S_1 + 2S_2^2 S_5 S_1 S_2 S_4 S_1 \\
& + 2S_2^2 S_3 S_4 S_1 S_2 S_3 S_1) + (2S_1 S_2 S_2 S_3 S_3 S_4 S_1 + 2S_1 S_2 S_2 S_3 S_4 S_5 S_1 + 2S_1 S_2 S_2 S_4 S_5 S_3 S_1 \\
& + 2S_1 S_2 S_2 S_4 S_3 S_3 S_5 S_1 + 2S_1 S_2 S_2 S_5 S_3 S_3 S_4 S_1 + 2S_1 S_2 S_2 S_5 S_4 S_3 S_3 S_1 + 2S_1 S_3 S_2 S_2 S_4 S_5 S_1 \\
& + 2S_1 S_3 S_3 S_4 S_2 S_2 S_5 S_1 + 2S_1 S_3 S_3 S_5 S_2 S_2 S_4 S_1 + 2S_1 S_3 S_3 S_2 S_2 S_5 S_4 S_1 + 2S_1 S_4 S_2 S_2 S_3 S_3 S_5 S_1 \\
& + 2S_1 S_5 S_2 S_2 S_3 S_3 S_4 S_1)
\end{aligned} \tag{6}$$

The above Equation is for a general air conditioning system modeled for five subsystems, which contains 120 terms. But the permanent function for the matrix Equation (5) corresponding to Figure 4.3, reduces to 24 terms. Because the variables  $S_{13}$ ,  $S_{14}$ ,  $S_{24}$ ,  $S_{25}$ ,  $S_{41}$ ,  $S_{42}$  and  $S_{52}$  values are 0 which means interactions are absent.

The variable permanent function for air conditioning system as shown in Figure 4.3 is

$$\begin{aligned}
\text{Per (G)} = & S_1S_2S_3S_4S_5 + (S_1S_2S_3S_4S_5S_4 + S_1S_2S_4S_3S_5S_3 + S_1S_2S_5S_3S_4S_3 + S_1S_4S_5S_2S_3S_2 \\
& + S_2S_3S_4S_1S_5S_5 + S_3S_4S_5S_1S_2S_2) + (S_1S_2S_3S_4S_5S_3 + S_1S_2S_3S_5S_4S_3 + S_2S_4S_1S_5S_3S_3 \\
& + S_4S_5S_1S_2S_2S_3S_3) + (S_1S_2S_3S_2S_4S_5S_4 + S_2S_1S_5S_1S_3S_4S_3 + S_3S_1S_2S_2S_4S_5S_4 + S_4S_1S_2S_2S_3S_5S_3 \\
& + S_4S_1S_5S_1S_2S_3S_3 + S_5S_1S_2S_2S_3S_4S_3) + (S_2S_1S_5S_4S_3S_3 + S_4S_1S_2S_2S_3S_5S_1 \\
& + S_4S_1S_5S_3S_3S_2S_2) + (S_1S_2S_2S_3S_4S_5S_3 + S_1S_2S_2S_3S_5S_4S_3 + S_4S_5S_4S_1S_2S_2S_3S_1) \\
& + (S_1S_5S_4S_3S_3S_2S_2)
\end{aligned} \tag{7}$$

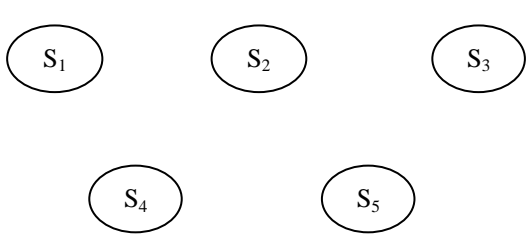
After substituting zero in some of the off-diagonal elements, the number of terms becomes reduced to 24, as shown in Equation (7). Every term of these equations represents a subset of the air conditioning system. It is possible to write these equations simply by visual inspection of the air conditioning system of Figure 4.3. To achieve this objective and for the unique representation and interpretation, the permanent function is written in a standard form as  $(N + 1)$  groups, where  $N$  is the number of subsystems. The permanent function when written in  $(N + 1)$  groups present an exhaustive way of analysis of an air conditioning system at different levels. The multinomial consists of different combinations of air conditioning system interaction components for example, structural constituents such as subsystem characteristics ( $S_i$ 's) and structural interactions ( $S_{ij}$ 's). The existence of elements such as  $S_{ij}^2$  or  $S_{ij} \cdot S_{ji}$ ,  $S_{ij} \cdot S_{jk} \cdot S_{ki}$ ,  $S_{ij} \cdot S_{jk} \cdot S_{kl} \cdot S_{li}$ , etc. correspond to the subsystems interacting in the form of a dyad, three subsystem loop, four subsystem loop, etc. respectively. The terms in each group of the multinomial form a separate group, which may be used for characterizing the air conditioning system uniquely. The permanent function has terms in different groups as follows:

- The first group contains only one term of thirteen isolated vertices  $S_i$ 's i.e. five components are to be considered together as independent entities.
- The second group is absent, because the component has no interaction with itself.

- The third group has ten terms, each term is a combination of dyad  $S_{ij}\cdot S_{ji}$ , loop and the component characteristic measure ( $S_i$ 's) of the remaining three unconnected components, for example ( $S_3S_4S_5 S_{12}S_{21}$ )
- The fourth group has 20 terms and each term consists of a three subsystem loop  $S_{ij}\cdot S_{jk}\cdot S_{ki}$ , and the component characteristic measure of the remaining two unconnected components  $S_i$ 's for example ( $S_4S_5S_{12}S_{23}S_{31}$ )
- The fifth group consists of two sub groups: the first subgroup has fifteen terms and each term is a set of two dyads and one independent subsystem; and the second subgroup has thirty terms and each term contains four subsystem loop that is,  $S_{ij}\cdot S_{jk}\cdot S_{kl}\cdot S_{li}$ , and one unconnected i.e independent subsystem
- The sixth group consists of two subgroups: first subgroup has one dyad ( $S_{ij}\cdot S_{ji}$ ) and three subsystem loop ( $S_{kl}\cdot S_{lm}\cdot S_{mk}$ ); and second subgroup consists of twenty-four five-subsystem loops i.e.  $S_{ij}\cdot S_{jk}\cdot S_{kl}\cdot S_{lm}\cdot S_{mi}$ .

In all, a general five subsystem permanent function will have  $5!$ , i.e. 120 terms arranged in  $(N + 1)$  groups. The terms in each group form a separate set, which may be used for characterizing the air conditioning system uniquely.

The real subsets of the total air conditioning system identified from Equation (7) may be represented as subgroups as in Figure 4.5, which provides graphical interpretation for visual understanding, analysis, and improvement of an air conditioning system.

<b>Physical meaning of different terms of Air Conditioning System Permanent Function</b>	
First Group	 <p>One term in 1<sup>st</sup> group</p>
Second Group	No Term

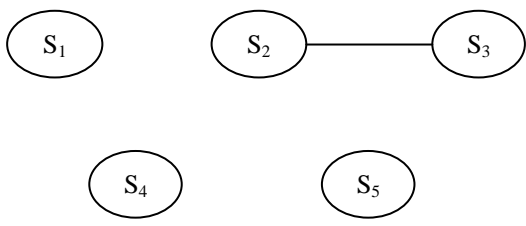
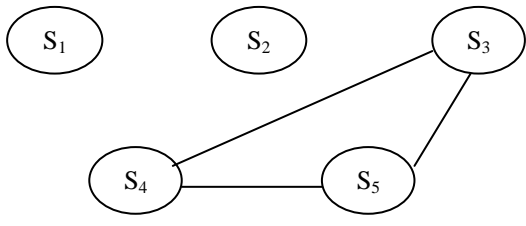
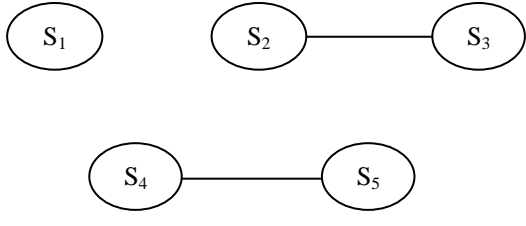
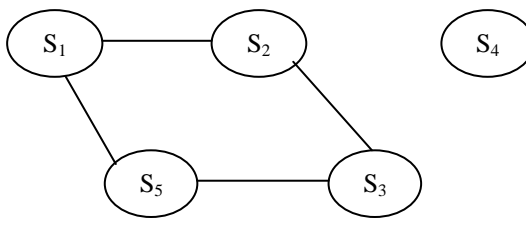
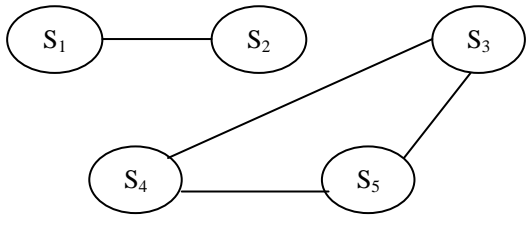
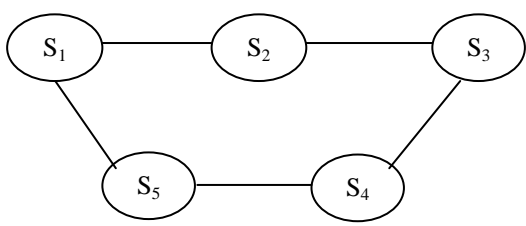
Third Group	 <p style="text-align: right;">+ five more terms</p>
Forth Group	 <p style="text-align: right;">+ three more terms</p>
Fifth Group (a)	 <p style="text-align: right;">+ five more terms</p>
Fifth Group (b)	 <p style="text-align: right;">+ two more terms</p>
Sixth Group (a)	 <p style="text-align: right;">+ two more terms</p>
Sixth Group (b)	 <p style="text-align: right;">+ one more term</p>

Figure 4.5 Graphical representation of air conditioning system multinomial

From the multinomial defined in Equation (6), a unique numerical index is derived and defined as:

$$\text{AC system numerical index} = \text{Per}(\mathbf{F}) \text{ (after substituting numerical values in the matrix } \mathbf{F}) \quad (8)$$

The numerical values to various subsystems as well as the interactions therein may be assigned, depending on the levels of performance in the dimension chosen for analysis i.e. according to the type of structural analysis. The dimension chosen for analysis may be efficiency, reliability, etc. For complex subsystems, the numerical values may be assigned by decomposing the subsystem into further lower comprehensive units and their permanent function may be used as the numerical score for the subsystem i.e. separate graph, matrix, or index can be derived for each subsystem using the same procedure. To get the exact degree of interactions, interdependencies, connectivity, etc. between the subsystems, we may have to consider the views of technical team experts. In certain cases, it may be possible to evaluate  $S_{ij}$ 's experimentally or using available mathematical models. This numerical index is considered as a composite score of total air conditioning system in any performance dimension depending upon the one selected for giving values to the individual structural constituents. This score can prove a powerful tool for comparison, ranking of different air conditioning systems and optimum selection of air conditioning system.

#### 4.7 Identification and Comparison of Air Conditioning System Structure

The air conditioning system permanent function is useful for identification and comparison of air conditioning system structures. The number of terms in each grouping of the air conditioning system permanent function for all kind of air conditioning systems for a given set of components will be same. However, their values will be different. Two air conditioning systems may be similar from the qualitative aspects, if their system structure graphs are isomorphic. Two such graphs are isomorphic, if they have identical permanent function matrix set representation. This means not only the number of terms in the groupings as well as sub-grouping as same but also their values are also same. Based on this, system structure identification set of air conditioning systems is represented as

$$[(J_1^T/J_2^T/J_3^T/J_4^T/J_{51}^T/J_{52}^T/J_{61}^T/J_{62}^T/\dots)(V_1^T/V_2^T/V_3^T/V_4^T/V_{51}^T/V_{52}^T/V_{61}^T+V_{62}^T/\dots)] \quad (9)$$

Where  $J_i^T$  represents the total number of terms in the 'ith grouping,  $J_{ij}^T$  represents the total number of terms of the  $J$ th subgrouping in the  $i$ th grouping. Similarly,  $V_i^T$  represents the

numerical value of the 'ith grouping and  $V_{ij}^T$  represents the numerical value of the jth subgrouping in the ith grouping. Numerical values of the  $S_i$ 's and  $S_{ij}$ 's are substituted in the subgrouping or the grouping to obtain the permanent system numerical index.

#### 4.8 Generalization of the permanent function model

For general air conditioning system with N subsystems, the air conditioning system characteristic and interdependence matrix,  $\mathbf{L}$  may be written as in Equation (10) below:

$$\mathbf{L} = \begin{bmatrix} S_1 & S_{12} & S_{13} & \dots & S_{1N} \\ S_{21} & S_2 & S_{23} & \dots & S_{2N} \\ S_{31} & S_{32} & S_3 & \dots & S_{3N} \\ \dots & \dots & \dots & \dots & \dots \\ S_{N1} & S_{N2} & S_{N3} & \dots & S_N \end{bmatrix} \quad (10)$$

For general N subsystem air conditioning system with all the subsystems linked together, the total number of terms of the permanent function shall be equal to N! The permanent for the above matrix, i.e.,  $\text{per}(\mathbf{L})$  is called variable permanent function. The variable permanent function for the above matrix is written in sigma ( $\Sigma$ ) form as

$$\begin{aligned} \text{Per}(\mathbf{L}) &= \prod_1^N S_i \\ &+ \sum_i \sum_j \sum_k \dots \sum_N (S_{ij} S_{ji}) S_k S_l \dots S_N \\ &+ \sum_i \sum_j \sum_k \dots \sum_N (S_{ij} S_{jk} S_{ki} + S_{ik} S_{kj} S_{ji}) S_l S_m \dots S_N \\ &+ \{ \sum_i \sum_j \sum_k \dots \sum_N (S_{ij} S_{ji}) (S_{kl} S_{lk}) S_m S_n \dots S_N \\ &\quad + \sum_i \sum_j \sum_k \dots \sum_N (S_{ij} S_{jk} S_{kl} S_{li} + S_{il} S_{lk} S_{kj} S_{ji}) S_m S_n \dots S_N \} \\ &+ \{ \sum_i \sum_j \sum_k \dots \sum_N (S_{ij} S_{ji}) (S_{kl} S_{lm} S_{mk} + S_{km} S_{ml} S_{lk}) S_n S_o \dots S_N \\ &\quad + \sum_i \sum_j \sum_k \dots \sum_N (S_{ij} S_{jk} S_{kl} S_{lm} S_{mi} + S_{im} S_{ml} S_{lk} S_{kj} S_{ji}) S_n S_o \dots S_N \} \\ &+ \dots \end{aligned} \quad (11)$$

These terms may be expanded into N + 1 groups. The interrelations which are not actually present in the air conditioning system may be given the value of 0 and thus eliminating the nonexistent terms. Finally, the terms of the permanent multinomial corresponding to the particular manufacturing system may be listed and the resulting graphs may be obtained and used for structurally analyzing the capabilities of the air conditioning system in different areas.

#### **4.9 Air Conditioning System Analysis**

The methodology described in the previous sections for complete analysis of air conditioning system is summarized in step-by-step manner as below:

1. Consider the desired air conditioning system. Study the complete air conditioning system and its subsystems (compressor, heat rejection system, heat absorption system, etc.), and also their interactions.
2. Logically develop a system graph of the air conditioning system with subsystems as vertices and edges for interaction between the vertices.
3. Using the graph in step 2, develop matrix similar to air conditioning system variable permanent matrix given in Equation (6). This matrix consists of  $S_i$ 's as diagonal elements and  $S_{ij}$  as edges or interactions.
4. Obtain air conditioning system permanent function i.e. multinomial similar to Equation (4), which considers all the subsystems simultaneously.
5. The numerical index of an air conditioning system would be obtained by substituting the numerical values of subsystems and their interactions. The numerical values depend on the type of structural analysis.
6. Various air conditioning systems can be compared on the basis of permanent numerical index thus obtained. Necessary improvement strategies may be implemented ahead for enhancing the dimension chosen for analysis of air conditioning system. The dimension may be efficiency, reliability, quality, etc.
7. From the different alternatives of air conditioning systems, the alternative with highest value of numerical index is the best choice for the given application satisfying all the product lifecycle issues.

#### **4.10 Usefulness of the Methodology**

The proposed procedure is useful for product design engineer, researcher, and industries at conceptual stage. This methodology is useful while

1. Making purchases of subsystems and interconnections at different levels from global market at the time of setting a company or manufacturing the product.
2. Carrying out cause and effect analysis to find out the reasons of poor quality, poor competitiveness etc.

3. Carrying out SWOT (Strength-Weakness-Opportunity-Threats) analysis before taking important and critical decisions.
4. Carrying out re-engineering of the product, process etc. for break through improvement.
5. Extending the product life time in the market.
6. Developing maintenance strategies.
7. The methodology is dynamic in nature as sub-systems/components and interactions, which appear as variables in different models may be changed without any difficulty.

From the above, it is clear that the graph theory and matrix approach as a decision-making method is relatively new, and offers a generic, simple, easy, and convenient decision-making method that involves less computation. In the permanent procedure, even a small variation in attributes leads to a significant difference in the selection index, and hence it is easy to rank the alternatives in the descending order, with clear-cut difference in the selection index. Further, the proposed procedure not only provides the analysis of alternatives, but also enables the visualization of various subsystems present and their interrelations, using graphical representation. The measures of the subsystems and their interactions with each other are used together to rank the alternatives, and hence provides a better evaluation of the alternatives. This methodology is not only useful for designers in development of reliable and robust air conditioning system but also to diagnose the failures of such systems.

#### **4.11 Application of Graph Theoretic Approach on existing air conditioning system**

To illustrate the effectiveness of the Graph Theoretical Approach, the study was made on an existing central air-conditioning system in a library building located at Thapar University, Patiala City.

##### **4.11.1 System Description**

This air conditioning unit is a Chilled Water system where refrigerant and water interaction takes place. The refrigerant in the shell of shell-and-tube heat exchanger evaporates by picking up the heat from the water which is in the tubes of the heat exchanger. This chilled water is then circulated to various water air heat exchangers called Fan coil Units/Air handling Units. The AHU is located much far from the plant room. In AHU blower fan blows the air on these chilled water coils and thus cooled air is circulated throughout the library

through the duct system. Return ducts are also available to return the hot air from library to the AHU room. Hence air loop is maintained between the library hall and AHU room. This system absorb the heat from the indoor space and rejects that heat to water which in turn may either reject heat cooling towers. Here the heat is extracted from the space and expelled to the outdoors (left to right) through 5 loops of heat transfer. The chilled water is produced in the evaporator of the refrigeration cycle and is passed through a multiple cooling coils. The heat is rejected through a water-cooled condenser and the condenser water pump sends it to the cooling tower. The cooling tower's fan drives air across an open flow of hot condenser water, transferring the heat to the outdoors. Figure 4.6 shows a conceptual view of this chilled water air-conditioning system.

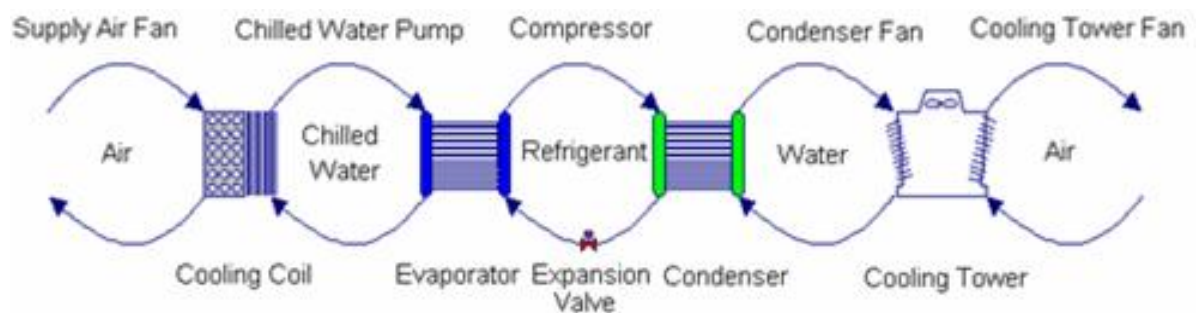


Figure 4.6 Different heat transfer loops in a Chilled Water System

The real picture of existing central air conditioning system with brief view of its main components is shown in Figure 4.7

#### 4.11.2 Structural Modeling and Analysis

By using Graph Theoretic Approach and by following the same procedure as discussed presented earlier, the modeling and analysis of existing air conditioning is presented. The central air conditioning system taken of study consists of a large number of components ranging from small thermostatic expansion valve to large cooling tower. In order to better understand the system along with its components and their interactions, schematic diagram of this library air conditioning system has been developed as shown in the Figure 4.8, which is useful for understanding the basic structure and functionality of an air conditioning system. All the interactions existing among the components are equally important in design and analysis of an air conditioning system. Schematic gives us a good visualization of interactions between the various components. The different colored lines show the flow of different

materials within the system in different loops. The flow of material is essential for the functionality of the air conditioning system.

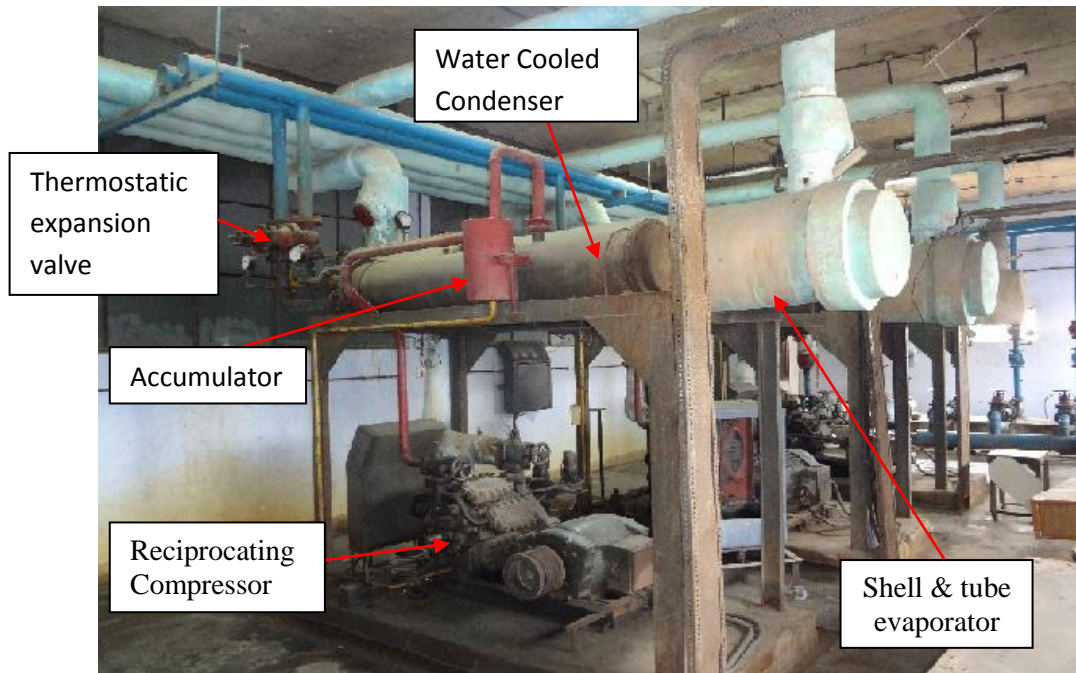


Figure 4.7 Chilled Water Central Air Conditioning System in library building of Thapar University, Patiala.

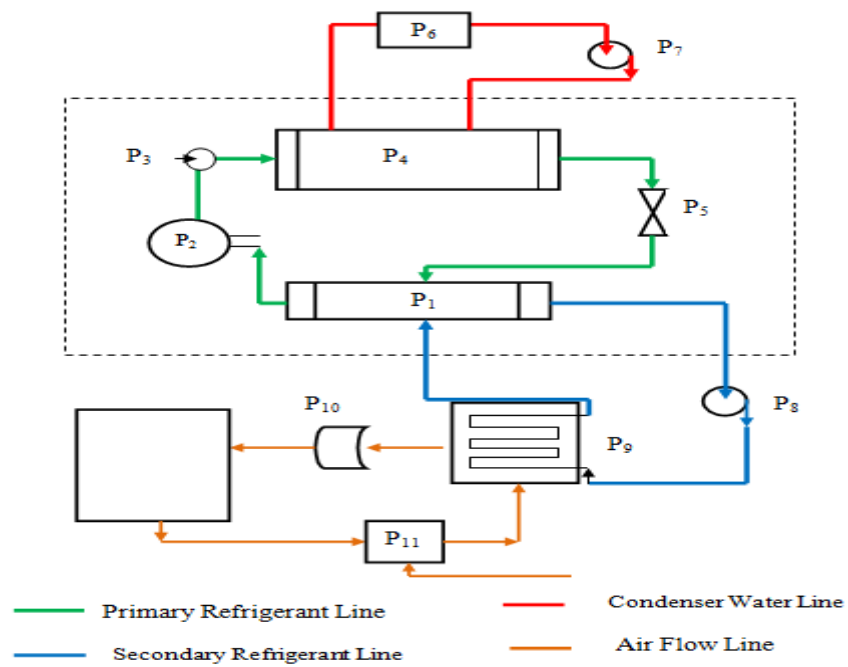


Figure 4.8 Schematic of Library air conditioning system

Here, P<sub>1</sub>=Evaporator, P<sub>2</sub> = Reciprocating Compressor, P<sub>3</sub>= Accumulator, P<sub>4</sub>= Shell and tube type Condenser, P<sub>5</sub>= Thermostatic Expansion Valve, P<sub>6</sub>= Cooling Tower, P<sub>7</sub>= Condenser water pump, P<sub>8</sub>= Evaporator Circulator Pump, P<sub>9</sub>= Cooling Coil, P<sub>10</sub>= Supply Fan, P<sub>11</sub>= Mixing box

These eleven main components are identified and as these components are physically attached to each other and there is exchange of material as well as energy between different components. So, interactions are critically important for functionality of air conditioning system. The various performance areas are dependent on the characteristics of the components and characteristics of their interactions. Interactions between the components are identified in the same manner as discussed earlier in this chapter, excluding the control type interactions. Here we are taking only physical subsystems under consideration. After following various steps of developed methodology for structural analysis, the undirected graph of the structure of the air conditioning system is developed as shown in Figure 4.9.

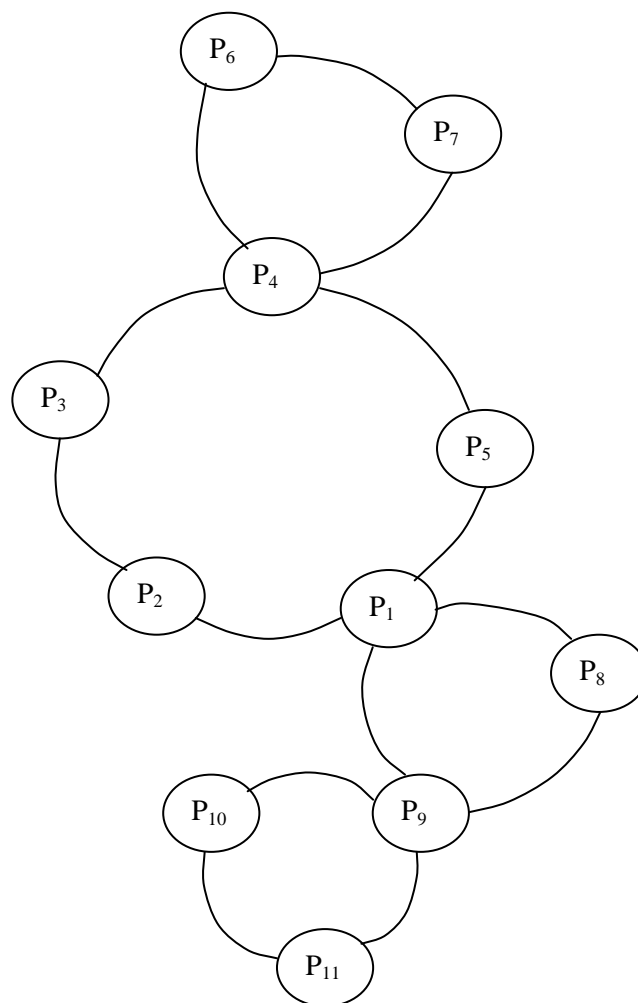


Figure 4.9 Undirected graph representation of the structure of Library air conditioning system

Now, the system structure matrix  $\mathbf{X}$  is constructed for this library air conditioning system. This matrix represents connectivity/interaction between different sub systems of air conditioning system. If the connectivity/interaction exists between two sub systems, it is represented by a binary number '1' and by '0' if there is no connectivity/interaction between two sub systems.

$$\begin{array}{cccccccccccc}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & \text{subsystems} \\
 \mathbf{X} = & \begin{bmatrix}
 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 0 \\
 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\
 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0
 \end{bmatrix} & & (12) \\
 & & & & & & & & & & & & \text{subsystems}
 \end{array}$$

Now, the variable permanent air conditioning system matrix corresponding to the eleven subsystems of air conditioning system as shown in graph (Figure 4.8) is developed as shown in Equation (13)

$$\begin{array}{cccccccccccc}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & \text{subsystems} \\
 \mathbf{Y} = & \begin{bmatrix}
 P_1 & P_{12} & 0 & 0 & P_{15} & 0 & 0 & P_{18} & P_{19} & 0 & 0 \\
 P_{21} & P_2 & P_{23} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & P_{32} & P_3 & P_{34} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & P_4 & P_4 & P_{45} & P_{46} & P_{47} & 0 & 0 & 0 & 0 \\
 P_{51} & 0 & 0 & P_{54} & P_5 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & P_{64} & 0 & P_6 & P_{67} & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & P_{74} & 0 & P_{76} & P_7 & 0 & 0 & 0 & 0 \\
 P_{81} & 0 & 0 & 0 & 0 & 0 & 0 & P_8 & P_{89} & 0 & 0 \\
 P_{91} & 0 & 0 & 0 & 0 & 0 & 0 & P_{98} & P_9 & P_{9,10} & P_{9,11} \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & P_{10,9} & P_{10} & P_{10,11} \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & P_{11,9} & P_{11,10} & P_{11}
 \end{bmatrix} & & (13) \\
 & & & & & & & & & & & & \text{subsystems}
 \end{array}$$

The Equation (13) is the variable permanent matrix of library air conditioning system, in which all the eleven components of air conditioning system are diagonal elements i.e.  $P_1, P_2, P_3, P_4, P_5, \dots, P_{11}$  and all the off-diagonal elements represents the interactions among these

components. This model of expression considers all the quantitative values of the subsystems and interactions after giving the '0' value to unconnected subsystems.

Now, using Equation (11) permanent function of library air conditioning can be developed. When the actual values of each term are substituted in the multinomial, the final values after the algebraic addition gives a numerical index, which can be considered as a score of total air conditioning system in any performance dimension depending upon the one selected for giving values to the individual structural constituents. This score can prove a powerful tool for comparison, ranking this library air conditioning system with other air conditioning systems. The numerical values to these eleven subsystems as well as the interactions therein may be assigned depending on the levels of the performance in the dimension chosen for analysis. The numerical values may be assigned by decomposing the subsystem into further lower comprehensive units and their permanent values for each subsystem variables  $P_1, P_2, P_3, P_4, P_5, \dots, P_{11}$  can be obtained. Thus, it gives complete structural evaluation of the air conditioning system as a single index. Work is in progress to carry out performance analysis of this library air conditioning system from different perspectives using this methodology.

#### 5.1 Conclusion

The foremost outcome of this work is that approaching the system, as a whole is absolutely indispensable in order to acquire a better picture of the operation of every system component and the interaction. The thesis is focused on modeling, evaluation, optimum selection and analysis of air conditioning system using system approach. Two different methodologies are presented to achieve the objectives of this work. Multi-Attribute Decision Making (MADM) approach is presented in Chapter 3 in order to achieve the objective of evaluation and optimum selection of air conditioning system from different alternatives. It identifies the various attributes needing to be considered for the optimum evaluation and selection of air conditioning systems. It also provides an n-digit coding scheme for air conditioning systems depicting the various attributes. It recognizes the need for, and processes the information about, relative importance of attributes for a given application without which inter-attribute comparison is not possible. It presents the result of the information processing in terms of a suitability index, which is used to rank the air conditioning in the order of their suitability for the given application. The contribution of the work regarding MADM approach can be summarized as

1. The proposed method provides a coding scheme, which is a collection of 173 attributes for characterization of air conditioning system and is useful in defining the air conditioning system accurately and precisely. The coding scheme is illustrated with the help of an example.
2. A 3-stage selection procedure including elimination search, TOPSIS approach and other graphical methods (line graph and spider diagram) on the basis of identified pertinent attributes and the separation of each alternative from generated hypothetically best and worst air conditioning systems, helps in ranking of all the air conditioning system alternatives.
3. The proposed methodology ensures that the selected air conditioning system is nearest to the hypothetical best air conditioning system and farthest from the hypothetical worst air conditioning system.

4. The developed methodology permits the consideration of both types of attributes such as larger-the-better and smaller-the-better together and provides the ranking accordingly.
5. Evaluation and ranking of an air conditioning system based on the mathematical and graphical approaches along with the illustrative examples are presented.
6. The final choice is to be made by carrying out the force field analysis.
7. It is recommended that the information about all the attributes related to an air conditioning system should be maintained as knowledge base for future usage by the manufacturer. This information will be helpful to himself apart from air conditioning system designer, maintenance personnel, user, etc.

Graph Theoretic Approach is presented in Chapter 4 in order to achieve the objective of developing the systems model for the structural analysis of air conditioning system. This model integrates the different constituents of the air conditioning system and describes the whole system. The contribution of the work regarding Graph Theoretic Approach can be summarized as:

1. This methodology builds a flexible and comprehensive model, which has the capability to consider the interactions between various components of the total air conditioning system.
2. The present work identifies five subsystems, which parameterize the air conditioning system. Also interactions between the components are identified under four different categories.
3. The systems methodology consists of the air conditioning system structure graph, the air conditioning system matrix, and air conditioning system permanent function. The system graph is the mathematical representation of the structural characteristics and their interactions, useful for visual modeling and analysis. The air conditioning system matrix converts graph into another mathematical form. This matrix representation is powerful tool for storage and retrieval of air conditioning systems in computer database.
4. The air conditioning system permanent function is a mathematical model characterizing the structure of the air conditioning system and also helps one to determine the air conditioning system numerical index. This numerical index is used for comparison, ranking, and optimum selection.

5. The model may serve as a framework for developing various quantitative performance indices in various dimensions of performance, viz. reliability, flexibility, quality, etc. giving an air conditioning system measure of the overall performance of the air conditioning system.

A case study of an existing central air-conditioning system in a library building located at Thapar University (Patiala) is also presented to illustrate the effectiveness of the Graph Theoretical Approach.

## **5.2 Future Scope**

1. A computer based electronic database for the storage and retrieval of different attributes of the air conditionings will be developed. This will make the selection procedure easy.
2. A computer program will be developed to carry out all the calculations in both the methodologies.
3. Cause and effect analysis and sensitivity analysis will be done to improve the quality and reliability of the air conditioning system.
4. An attempt will be made to develop various quantitative performance indices in various dimensions of performance such as reliability, efficiency, quality, etc.
5. Graph Theoretic Approach will be developed to analyze the air conditioning system by obtaining the permanent functions at the system as well as subsystem levels.
6. The case study on existing central air conditioning system is discussed in this thesis. So research can be carried out on more practical applications.

## REFERENCES

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- [1] Edward G. Pita, "Air Conditioning Principles and Systems", 4<sup>th</sup> edition, Pearson Education, New York, 2003.
- [2] Lesson 1 History of refrigeration, version 1 ME, IIT Kharagpur, <http://nptel.iitm.ac.in/courses/Webcoursecontents/IITKharagpur/Ref and Air Cond /pdf/RACLecture1.pdf>
- [3] V. Paul Lang, "Principles of Air Conditioning", 3<sup>rd</sup> edition, CBS Publishers and distributors.
- [4] Monohar Prashad, "Refrigeration and Air Conditioning Data Book", New Age International Publishers.
- [5] Andrew D. Althouse, Carl H. Turnquist and Alfred F. Braccino", Modern Refrigeration and Air Conditioning",
- [6] <http://finance.yahoo.com/news/india-air-conditioners-market-forecast-160500680.html>
- [7] Economical Services Group-National Productivity Council, "Productivity and competitiveness of Light Electrical Industry in India", New Delhi.
- [8] Piotr A. Domanski, "Conference Report: Refrigerants for the 21st century ASHRAE/NIST refrigerants conference Gaithersburg, MD October 6-7, 1997", *Journal of Research of the National Institute of Standards and Technology*, 1998, 103(5), pp. 529- 533.
- [9] Sandy Halliday, Clive Beggs IV & Tariq Muneer, "Is solar air conditioning feasible?" *Building Research & Information*, 1999, 27(3), pp. 149-164.
- [10] Malcolm R. Stout Jr. PE & James W. Leach PE, "Cooling Tower Fan Control for Energy Efficiency", *Energy Engineering*, 2002, 99(1), pp. 7-31.
- [11] Dr C. Lertsatitthanakorn, Dr J. Hirunlabh, Dr J. Khedari & M. Daguene, "Experimental performance of a ceiling-type free convected thermoelectric air conditioner", *International Journal of Ambient Energy*, 2002, 23(2), pp. 59-68.
- [12] Shabbir H. Gheewala & Per H. Nielsen, "Central and individual air-conditioning systems - A comparison of environmental impacts and resource consumption in a life cycle perspective", *International Journal of Sustainable Development & World Ecology*, 2003, 10(2), pp. 149-155.
- [13] H. Han & S. M. Deng, "A Study on Residential Clothes Drying Using Waste Heat Rejected from a Split-Type Room Air Conditioner (RAC)", *Drying Technology: An International Journal*, 2003, 21(8), pp. 1471-1490.

- [14] Michael K. West & Glenn C. Haynes, “Desiccant Dehumidification Performance Lessons”, *Energy Engineering*, 2003, 100(3), pp. 9-14.
- [15] David MacPhaul, “The Basics of HVAC Systems in Humid Climates - What Goes Wrong and Why”, *Energy Engineering*, 2003, 100(3), pp. 31-38.
- [16] Charles J. Cromer, “Test Results of Energy Savings and Humidity Control Devices”, *Energy Engineering*, 2003, 100(3), pp. 15-30.
- [17] Esam Elsarrag, Elsheikh Elmagzoub M. Ali & Sanjeev Jain, “Design Guidelines and Performance Study on a Structured Packed Liquid Desiccant Air-Conditioning System”, *HVAC&R Research*, 2005, 11(2), pp.319-337.
- [18] Yaw-Shyan Tsay, Shinsuke Kato, Ryoza Ooka, Makoto Koganei, Kousaku Nishida & Koichi Kawamoto, “Study on Noncondensing Air-Conditioning System Performance When Combining a Desiccant Cooling System with a CO<sub>2</sub> Heat Pump”, *HVAC&R Research*, 2006, 12(S3), pp.917-933.
- [19] Clito F.A. Afonso, “Recent advances in building air conditioning systems”, *Applied Thermal Engineering*, 2006, 26, pp. 1961–1971.
- [20] A. Qiu Haitao, B. Wu Yan and C. Sun Shouqian, “Green Air-conditioner Design”, *Seventh International Conference on Computer-Aided Industrial Design and Conceptual Design*, Hangzhou, 2006, pp. 1–4.
- [21] CAO Guoqing and TU Guangbei, “Optimization of selecting air conditioning cold/heat sources with Grey Relation Analysis”, *Transactions of Tianjin University*, 2006, 12, pp.229–234.
- [22] W. L. Tse & Albert T.P. So, “The Importance of Human Productivity to Air-Conditioning Control in Office Environments”, *HVAC&R Research*, 2007, 13(1), pp. 3-21.
- [23] Zhuang Wu, Roderick V.N. Melnik, Finn Borup, “Model-based analysis and simulation of airflow control systems of ventilation units in building environments”, *Building and Environment*, 2007, 42, pp. 203–217.
- [24] Ahmed Hamza H. Ali & Ibrahim M. Ismail, “Evaporator Air-Side Fouling: Effect on Performance of Room Air Conditioners and Impact on Indoor Air Quality”, *HVAC&R Research*, 2008, 14(2), pp. 209-219.
- [25] Mahendra Kumar, I.N. Kar & Anjan Ray, “State Space Based Modeling and Performance Evaluation of an Air-Conditioning System”, *HVAC&R Research*, 2008, 14(5), pp. 797-816.

- [26] R. G. Kapadia, Sanjeev Jain & R. S. Agarwal, "Transient Characteristics of Split Air-Conditioning Systems Using R-22 and R-410A as Refrigerants", *HVAC&R Research*, 2009, 15(3), pp. 617-649.
- [27] Risto Ciconkov & Zahid H. Ayub, "New Technologies in Ammonia Refrigerating and Air-Conditioning Systems", *Heat Transfer Engineering*, 2009, 30(4), pp. 324-329.
- [28] Ramesh K. Shah (2009), "Automotive Air-Conditioning Systems - Historical Developments, the State of Technology, and Future Trends", *Heat Transfer Engineering*, 2009, 30(9), pp. 720-735.
- [29] Liu Jiayou and Zhao Yanxin, "Application of Value Engineering in Selection of Villa Air-conditioning System", *International Conference on Information Management, Innovation Management and Industrial Engineering*, 2009, 2, pp. 517-520.
- [30] Xiaoping Feng and Zhifang Gu, "Internet-based decision-making System of air-conditioning cooling and heating source", *Fifth International conference on Natural Computation*, 2009, 4, pp. 316-318.
- [31] Changxing Zhang and Songtao Hu, "Fuzzy Multi-Criteria Decision Making for selection of schemes on cooling and heating source", *Seventh International Conference on Fuzzy Systems & Knowledge Discovery, Yantai, Shandong*, 2010, pp. 876-878.
- [32] Wei Bing, Yang Huayi and Wei Zhe, "Industrial Electronics and Applications-ICIEA", *Fifth IEEE Conference on Industrial Electronics and Applications-ICIEA, Taichung*, 2010, pp. 857-860.
- [33] Hui-qing LIU and Han-dong LIU, "A fuzzy multi-attribute group decision making model and its application to selection of air conditioning cold/heat source", *International Conference on System Science, Engineering Design and Manufacturing Information, Yichang*, 2010, 1, pp. 151-154.
- [34] Dr. S.C. Kaushik, Mr. N.L. Panwar, and Mr. V. Reddy Siva, "Thermodynamic analysis and evaluation of heat recovery through a canopus heat exchanger for vapour compression refrigeration (VCR) system." *Journal of Thermal Analysis and Calorimetry*, 2011, DOI: 10.1007/s10973-011-2111-7.
- [35] Ashish Bhateja, V.P. Agrawal and K. Athre, "Total Design Concept of Springs – A novel Approach Using MADM Methodology", *Advances in Mechanical Engineering*, 1996, pp. 401-424.
- [36] P.P. Bhangale, V.P. Agrawal, S.K. Saha, "Attribute based specification, comparison and selection of a robot", *Mechanism and Machine Theory*, 2004, 39, pp. 1345-1366.

- [37] R. T. Durai Prabhakaran, B. J. C. Babu & V. P. Agrawal, "Optimum Selection of a Composite Product System Using MADM Approach", *Materials and Manufacturing Processes*, 2006, 21(8), pp. 883-891.
- [38] R.K. Garg, V.P. Agrawal, and V.K. Gupta, "Coding, evaluation and selection of thermal power plants – A MADM approach", *Electrical Power and Energy Systems*, 2007, 29, pp. 657–668.
- [39] C. Phaneendra Kiran, Shibu Clement, and V.P. Agrawal, "Coding, evaluation and optimal selection of a mechatronic system", *Expert Systems with Applications*, 2011, 38, pp. 9704-9712.
- [40] R.K. Garg, V.P. Agrawal and V.K. Gupta, "Selection of power plants by evaluation and comparison using graph theoretic methodology", *Electrical Power and Energy Systems*, 2006, 28, pp. 429-435.
- [41] R.T. D. Prabhakaran and V.P. Agrawal, "Structural Modeling and Analysis of Composite Product System: A Graph Theoretic Approach", *Journal of Composite Materials*, 2006, 40(22), pp. 1987-2007.
- [42] Varinder Singh and V.P. Agrawal, "Structural modelling and integrative analysis of manufacturing systems using graph theoretic approach", *Journal of Manufacturing Technology Management*, 2008, 19(7), pp. 844-870.
- [43] C.P. Kiran, Shibu Clement and V.P. Agrawal, "Design for X-Abilities of a Mechatronic System- A Concurrent Engineering and Graph Theory Based Approach", *Concurrent Engineering: Research and Applications*, 2011, 19(1), pp. 55-69.
- [44] N. Deo , "Graph theory with application to engineering and computer science," Engle Wood Cliff, NJ: Prentice Hall; 1974.
- [45] R. Venkataswamy and V.P. Agrawal, "System and Structural Analysis of an Automobile Vehicle – A Graph theoretic Approach," *International Journal of Vehicle Design*, 1995, 16 (4/5), pp. 477-503.
- [46] V.P. Agrawal and J.S. Rao, "Structural classification of kinematic chains and mechanisms," *Mech Mach Theory*, 1989, 24 (4), pp. 309-21.
- [47] W.B. Jurkat and H.J. Ryser, "Matrix Factorization of Determinants and Permanents," *Journal of Algebra*, 1996, 3(1), pp. 1-27.
- [48] Roger W. Hains and C. Lewis Wilson, "HVAC Systems Design Handbook", Second Edition, McGraw Hill Inc.

[49] Ali Vedavarz, Sunil Kumar and Muhammed Iqbal Hussain, “HVAC: Handbook of Heating, Ventilation and Air Conditioning for Design and Implementation”, Industrial Press Inc., New York, 2007.