This chapter provides a computationally simple and efficient methodology for evaluating the attributes of a power plant and to select the best plant based on this evaluation. First, the graphical model of the power plant is developed, where the various attribute of the plant and their interactions/interdependencies are represented by an attribute digraph. Then, the mathematical model of the plant is developed. In mathematical model the attribute digraph is converted into matrix model in order to have a computational method to evaluate the plants in terms of their ranking and optimal selection. Further, the matrix model is represented by a permanent function which yields the suitability index \([SI]\) of the plant. The suitability index is the value of the permanent of the attribute matrix. The plants are ranked in accordance to their \(SI\) value in the descending order. The plant with rank one has been taken as the best suitable plant in view of the users requirements. Sensitivity analysis is carried out to identify the most dominating attributes of the plant that affect its overall suitability index. A comprehensive comparison of the potentially suitable alternative plants is made using graphs and histograms to better educate the user/decision maker. The methodology and the procedure are illustrated by an example.

6.1 INTRODUCTION

The march from the primitive human, through the Stone Age, Bronze Age, Iron Age, the industrial revolution and to the current technological age has been characterized by decreasing dependence on man power but increasing dependence on the use of energy. The energy in the form of electricity is most desired as it is easy to transport and control, clean in its surroundings and easily convertible to heat or work. Today the energy is synonymous with progress. The availability of energy not in adequate quantities can balk the entire economic activity of a country. In India, dismal performance of power plants has adversely hit the industrial activity- the cost has shot up and industrial sickness has assumed alarming proportions. The most important
reasons for this poor availability of energy are under utilization of productive capacity and poor overall performance of power plants. Present state of the art in the field of power plants does, in fact, represent a stimulating challenge for engineers because of their optimum selection in regard to various attributes like technical, socio-economical, environmental etc. These attributes are of different and conflicting nature.

Design is considered as the total activity necessary to provide an interface to meet a market need. It commences with the identification of the need and is not complete until the product is in use, providing an acceptable level of performance. In this world of globalization and competition, it is difficult to properly identify the product. Factors, that influence the product environment, are many, varied and interactive. In order to accommodate these factors and assess their influence on a particular system, it has been found essential to identify various attributes and their interdependence and then finalize a coding structure for each of the plant so that they can be compared very easily with each other for different end uses. In this work, different attributes were identified and classified quantitatively and/or qualitatively and coded in order to have a new way of representing specifications of a thermal power plant. Such a coding structure of a thermal power plant has been termed as "AutoCode" in chapter - 5. This coding structure provides complete information about the attributes of the thermal power plant.

So far the researchers have not found such a graphical and mathematical analysis for comparison and optimum selection of thermal power plants. Kusiak and Wang [1993] have developed an algorithm for organizing design activities in order to effectively produce an acceptable design, representing them by incidence matrix and corresponding directed graph. Lou [1984] has discussed economic feasibility of thermal power plants taking into consideration local conditions and resources. Guidelines were given for selection of optimum location, size and type of equipments for thermal power plants. Wang and Min [2000] have developed an integrated resource-planning model for utilities with outage costs. Agrawal et al. [1992] have used multiple attribute decision-making method for evaluation and selection of optimum grippers.
Graph Theory has been applied extensively in various disciplines to evaluate and analyze the systems in terms of their characteristics. Badiru [1990] explained a system approach to TQM by considering all the interactions necessary between various elements of the organization including people and machines. Abdulla and Knight [1994] presented an approach, which enabled the designer to ensure that the manufactured product with existing facilities is of better quality. Gandhi et al. [1991] used graph theory to develop an evaluation methodology for system reliability and was later used by Gandhi and Agrawal [1994] to evaluate and analyze the system.

The literature available on selection, mathematical models of power plants and their salient characteristics useful for analysis have been presented by Baur [1983], Kordan [1984] and Gandhi and Agrawal [1994]. Selot [1986], Gupta et al. [1989], Hobbs and Centolella [1995] and Matto [1997] etc. have studied the effects of economic aspects of maintenance and operation, meteorological factors, environmental policies and coal quality on the overall performance of a power plant, respectively. The literature survey as cited above reveals that though the effect of individual parameters have been discussed by different researchers but all such factors have not been considered all together in a unified manner. So a need was felt to develop a unified approach which would enable thermal power plant development team to consider all the aspects from concepts to disposal of its life cycle concurrently and in an integrated manner for optimum selection of a power plant.

In this Chapter, Graph Theoretical Methodology (GTM) is used to analyze and evaluate the various alternative plants. These plants are ranked in ascending or descending order based on their suitability index. A comprehensive comparison of the alternative plants is also made using graphs and histograms.

6.2 METHODOLOGY ADOPTED

The Graph Theoretical Methodology that combines various attributes relevant to a thermal power plant into a single measure so that a comprehensive ranking of the alternative plants could be made has been discussed in Chapter – 3. The same methodology is adopted for evaluation, ranking and selection of various alternative plants used for electricity generation. This methodology comprises of two phases. In the first phase, graphical model of the system is prepared which is named as
"Attribute Digraph" in this Chapter. In the second phase, the graphical model is converted into matrix model called as "Attribute Matrix" and then this matrix is expressed in the form of a function called "Variable Permanent Function (VPF)".

6.2.1 Attribute Digraph

The various attributes and their interconnectivities that control the optimum selection of a power plant have been identified in chapter - 5 and the same are expressed here in terms of nodes and edges, respectively. Then, 'Attribute Digraph' is constructed using these nodes and edges. The nodes and the edges in the attribute digraph, respectively, represent the ratings and the relative importance of the attributes of a power plant for a particular application. For example, a node \((A_i)\) in the attribute digraph gives the rating of \(i^{th}\) attribute and the edge \((a_{ij})\) gives the relative importance of \(j^{th}\) attribute in respect of \(i^{th}\) attribute. The attribute digraph developed for a thermal power plant (TPP) having five attributes is given in Fig. - 6.1.

\[
\begin{array}{c}
1 \\
5 \\
3 \\
2 \\
4 \\
\end{array}
\]

ATTRIBUTE DIGRAPH FOR A TPP WITH FIVE ATTRIBUTES

FIGURE – 6.1

6.2.2 Attribute Matrix

Since the attribute digraph is not suitable for computer processing, matrix method is used to represent the attribute digraph by an equivalent matrix named as 'Attribute Matrix'. The size of this matrix will be \(n \times n\) corresponding to an attribute digraph containing \(n\) attributes (nodes). The diagonal elements \((a_{ii})'s\) and the off-diagonal elements \((a_{ij})'s\) of this matrix give the attribute ratings and their relative importance respectively. Thus, the attribute matrix is a combination of two matrices named as 'Attribute Rating Matrix' and 'Attribute Relative Importance Matrix'.

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6.2.2.1 Attribute Rating Matrix

The attribute rating matrix represents the ratings of various attributes in a power plant. Since these attribute ratings are different for different systems/power plants for a given application, hence, the attribute rating matrix differs from system to system. The attribute rating matrix corresponding to 'n' attributes can be written as:

\[
\begin{bmatrix}
  a_{11} & 0 & 0 & 0 & \ldots & 0 \\
  0 & a_{22} & 0 & 0 & \ldots & 0 \\
  0 & 0 & a_{33} & 0 & \ldots & 0 \\
  0 & 0 & 0 & a_{44} & \ldots & 0 \\
  \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\
  0 & 0 & 0 & 0 & \ldots & a_{nn}
\end{bmatrix}
\]

(6.1)

All the off diagonal elements are zero because they represent the relative importance of the attributes.

The attribute rating for a case when the minimum threshold value of an attribute is specified in the problem statement may be determined as:

\[
a_{ii} = \frac{\text{Value of } i^{th} \text{ attribute} - \text{Minimum threshold value of } i^{th} \text{ attribute}}{\text{Max. value of } i^{th} \text{ attribute in database} - \text{Min. threshold value of } i^{th} \text{ attribute}}
\]

(6.2)

The attribute rating for a case when the maximum threshold value of an attribute is specified in the problem statement may be determined as:

\[
a_{ii} = \frac{\text{Max. threshold value of } i^{th} \text{ attribute} - \text{Value of } i^{th} \text{ attribute}}{\text{Max. threshold value of } i^{th} \text{ attribute} - \text{Min. value of } i^{th} \text{ attribute in database}}
\]

(6.3)

6.2.2.2 Attribute Relative Importance Matrix

The attribute relative importance matrix is formed on the basis of the relative importance of various attributes for a particular application. The attribute relative importance matrix corresponding to n attributes can be written as:
The values of $a_{ij}$ are decided based on the information obtained from the user. Table - 6.1 which has been prepared for a scale of $[0, 1]$ may be used as an aid while deciding these values. Here, in this Table $a_{ij} = 1 - a_{ji}$, where $a_{ij}$ represents the relative importance of $j^{th}$ attribute with respect to $i^{th}$ attribute and $a_{ji}$ represent the relative importance of $i^{th}$ attribute with respect to $j^{th}$ attribute. It is not necessary that the relative importance of the attributes i.e. $a_{ij}$ and $a_{ji}$ will follow a particular relationship such as $a_{ij} = 1 - a_{ji}$ or $a_{ij} = 1/a_{ji}$. These values can also be evaluated independently.

The attribute matrix is a complete representation of attribute digraph and can be written, by adding attribute rating matrix and attribute relative importance matrix, as:

$$
\begin{bmatrix}
0 & a_{12} & a_{13} & a_{14} & \cdots & a_{1n} \\
a_{21} & 0 & a_{23} & a_{24} & \cdots & a_{2n} \\
a_{31} & a_{32} & 0 & a_{34} & \cdots & a_{3n} \\
a_{41} & a_{42} & a_{43} & 0 & \cdots & a_{4n} \\
\vdots & \vdots & \vdots & \vdots & \cdots & \vdots \\
a_{n1} & a_{n2} & a_{n3} & a_{n4} & \cdots & 0 \\
\end{bmatrix}
\quad \quad \quad \quad \quad (6.4)
$$

All diagonal elements of this matrix are zero because there is no significance of comparing an attribute with respect to itself.

$$
\begin{bmatrix}
0 & a_{12} & a_{13} & a_{14} & \cdots & a_{1n} \\
a_{21} & 0 & a_{23} & a_{24} & \cdots & a_{2n} \\
a_{31} & a_{32} & 0 & a_{34} & \cdots & a_{3n} \\
a_{41} & a_{42} & a_{43} & 0 & \cdots & a_{4n} \\
\vdots & \vdots & \vdots & \vdots & \cdots & \vdots \\
a_{n1} & a_{n2} & a_{n3} & a_{n4} & \cdots & 0 \\
\end{bmatrix}
\quad \quad \quad \quad \quad (6.5)
$$

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**TABLE – 6.1**

**RELATIVE IMPORTANCE OF \( i^{th} \) ATTRIBUTE OVER \( j^{th} \) ATTRIBUTE (ON A SCALE OF 0 TO 1)**

<table>
<thead>
<tr>
<th>S. NO.</th>
<th>CASE DESCRIPTION</th>
<th>( a_i )</th>
<th>( a_{ij} = 10 - a_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Two attributes equally important</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>One attribute slightly more important than other</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>3</td>
<td>One attribute more important than other</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>4</td>
<td>One attribute very important than other</td>
<td>0.8</td>
<td>0.2</td>
</tr>
<tr>
<td>5</td>
<td>One attribute exceptionally important than other</td>
<td>0.9</td>
<td>0.1</td>
</tr>
<tr>
<td>6</td>
<td>One attribute most important, other not important</td>
<td>1.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
6.2.3 Permanent Function Representation

Variable Permanent Function or simply termed as Permanent is a standard matrix function that is used in combinatorial mathematics. It is a powerful tool for the attribute based evaluation, ranking in ascending or descending order and optimum selection of the power plants. The variable permanent function of an attribute matrix, known as Attribute Variable Permanent Function (AVPF), is a complete representation of the attributes of a power plant. It retains all possible information of the attributes and their interconnectivities. The quantitative value of AVPF is obtained by substituting the numerical values of each element of the attribute matrix in the AVPF itself. This numerical value is called as the Suitability Index and is used to rank all alternative power plants. Computer software has been developed to find the suitability index of the power plant and its details are given in Annexure – III.

The attribute variable permanent function for ‘n' attributes digraph, when expanded, will have (n!) terms. These terms may be arranged in (n + 1) groups and the physical meaning associated with each term can be interpreted as explained in Section 3.4.3 and 3.4.4 of Chapter – 3. The details of the terms appearing in the expression of AVPF such as groups/subgroups, number of terms and their respective sub digraphs for a five attributes digraph shown in Fig. – 6.1 are given in Fig. – 6.2.

6.3 COMPUTER SOFTWARE PACKAGE

A computer software package has been developed for GTM. It has been written in turbo ‘C' and runs on a personal computer under Microsoft disc operating system using turbo ‘C' compiler. This program has been tested to obtain the output for 190 attributes which were considered in chapter – 5 using hypothetical test data. These attributes are not reiterated here to avoid repetition. The computer code for this software package is given in Annexure – III. The algorithm is written as:

ALGORITHM PERMAN

\[(\text{A})\quad P \leftarrow 0; X_i \leftarrow a_{ii} - 1/2 \sum_{j=1}^{n} a_{ij} (i = 1, n); \ sgn \leftarrow -1\]

\[(\text{B})\quad sgn \leftarrow - sgn; P \leftarrow sgn, \text{ get next subset of (1,2,\ldots,n-1)}\]

from NEXSUB; if empty, to (c); if j was deleted,
<table>
<thead>
<tr>
<th>Group</th>
<th>No. of Terms</th>
<th>Terms</th>
<th>Sub-Digraph</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>a₁₁ a₂₂ a₃₃ a₄₄ a₅₅</td>
<td>A₁° A₂° A₃° A₄° A₅°</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>a₁₂ a₂₁ a₃₃ a₄₄ a₅₅ a₁₃ a₃₁ a₂₂ a₄₄ a₅₅ etc.</td>
<td>A₁ -- A₂ -- A₃° A₄° A₅°</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>a₁₂ a₂₃ a₃₁ a₄₄ a₅₅ a₁₃ a₃₂ a₂₁ a₄₄ a₅₅ etc.</td>
<td>A₁ -- A₂ Triangle A₃ A₄° A₅°</td>
</tr>
<tr>
<td>5a</td>
<td>30</td>
<td>a₁₂ a₂₃ a₃₄ a₄₁ a₅₅ a₁₂ a₂₃ a₃₅ a₅₁ a₄₄ etc.</td>
<td>A₁ -- A₂ -- A₃ -- A₄ -- A₅°</td>
</tr>
<tr>
<td>5b</td>
<td>15</td>
<td>a₁₂ a₂₁ a₃₄ a₄₃ a₅₅ a₁₂ a₂₁ a₃₅ a₅₃ a₄₄ etc.</td>
<td>A₁ -- A₂ -- A₃ -- A₄° A₅°</td>
</tr>
<tr>
<td>6a</td>
<td>20</td>
<td>a₁₂ a₂₁ a₃₄ a₄₅ a₅₃ a₁₂ a₂₁ a₃₅ a₅₄ a₄₃ etc.</td>
<td>A₁ -- A₂ Triangle A₃ -- A₄ -- A₅</td>
</tr>
<tr>
<td>6b</td>
<td>24</td>
<td>a₁₂ a₂₃ a₃₄ a₄₅ a₅₁ a₁₂ a₂₃ a₃₅ a₅₄ a₄₁ etc.</td>
<td>A₁ -- A₂ -- A₃ -- A₄ -- A₅</td>
</tr>
</tbody>
</table>

**GRAPHICAL REPRESENTATION OF THE TERMS OF VARIABLE PERMANENT FUNCTION**

**FIGURE – 6.2**

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z ← -1; otherwise, z ← 1;

\[ x_i \leftarrow x_i + z a_{ij} \quad (i = 1, n) \]

(C) \[ P \leftarrow P \cdot x_i \quad (i = 1, n); \quad p \leftarrow p + P; \text{ if more subsets remain,} \]

to (B); Permanent \leftarrow 2 (-1)^{n-1} p; EXIT.

**ALGORITHM NEXSUB**

(A) [First entry] \[ m \leftarrow 1; j \leftarrow 1; z \leftarrow 1; \text{exit.} \]

(B) Later entry \[ m \leftarrow m + 1; x \leftarrow m; j \leftarrow 0. \]

(C) \[ j \leftarrow j + 1; x \leftarrow x/2; \text{ if } x \text{ is an integer, to (C).} \]

(B) \[ z \leftarrow (-1)^{x+1/2}; \text{ if } m = 2^n, \text{ final exit; EXIT.} \]

### 6.4 ILLUSTRATIVE EXAMPLE

This methodology is applied for the example problem discussed in Chapter - 5 for illustration and to compare with Multiple Attribute Decision Making (MADM) methodology. The ‘Database’ that has already been provided in Table - 5.15 with max. and min. threshold values for each attribute is reproduced for ready reference as:

<table>
<thead>
<tr>
<th>NAME OF THE PLANT</th>
<th>CAPACITY MW</th>
<th>COST/MW X10^3 (Rs.)</th>
<th>EGC</th>
<th>PLF %age</th>
<th>ROR %age</th>
<th>P. Level Man/MW</th>
<th>SAF</th>
<th>AES</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>500</td>
<td>2.5</td>
<td>1.50</td>
<td>80</td>
<td>10.0</td>
<td>0.8</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>B</td>
<td>440</td>
<td>2.7</td>
<td>1.40</td>
<td>93</td>
<td>11.0</td>
<td>0.9</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>C</td>
<td>500</td>
<td>3.5</td>
<td>1.20</td>
<td>90</td>
<td>12.5</td>
<td>1.0</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>D</td>
<td>220</td>
<td>3.0</td>
<td>1.00</td>
<td>92</td>
<td>14.0</td>
<td>1.2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>E</td>
<td>220</td>
<td>2.0</td>
<td>1.50</td>
<td>90</td>
<td>12.0</td>
<td>1.4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>I</td>
<td>500</td>
<td>2.8</td>
<td>1.30</td>
<td>85</td>
<td>9.0</td>
<td>1.3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>J</td>
<td>500</td>
<td>3.5</td>
<td>1.25</td>
<td>78</td>
<td>10.5</td>
<td>1.5</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Threshold Values</td>
<td>Max. --</td>
<td>3.5</td>
<td>1.50</td>
<td>--</td>
<td>--</td>
<td>1.5</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Min. 220</td>
<td>--</td>
<td>70</td>
<td>8</td>
<td>--</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

**Solution**

1. The diagonal elements (a_{ii}) of the attribute rating matrix for each power plant are determined using Eqs. - 6.2 & 6.3, whichever is applicable. These diagonal elements for power plant ‘A’ are calculated as under:

(a) The ratings for the attributes namely, ‘capacity’, ‘PLF’, ‘ROR’, ‘safety’ and ‘aesthetics’ for which the minimum threshold values are specified in the problem statement is calculated using Eq. - 6.2 and are given as:
(a) The ratings for the attributes namely, 'cost', 'electricity generation cost' and 'P. level' for which the maximum threshold values are specified in the problem statement is calculated using Eq. – 6.3 and are given as:

\[
a_{22} \text{(Cost)} = \frac{(3.5 \times 10^8 - 2.5 \times 10^8)}{(3.5 \times 10^8 - 2.0 \times 10^8)} = 1.0 / 1.5 = 0.67
\]

\[
a_{33} \text{(EGC)} = \frac{(1.5 - 1.5)}{(1.5 - 1.0)} = 0.0 / 0.5 = 0.00
\]

\[
a_{66} \text{(P. Level)} = \frac{(1.5 - 0.8)}{(1.5 - 0.8)} = 0.7 / 0.7 = 1.00
\]

(b) The ratings for the attributes namely, ‘cost’, ‘electricity generation cost’ and ‘P. level’ for which the maximum threshold values are specified in the problem statement is calculated using Eq. – 6.3 and are given as:

\[
a_{11} \text{(Capacity)} = \frac{(500 - 220)}{(500 - 220)} = 280 / 280 = 1.00
\]

\[
a_{44} \text{(PLF)} = \frac{(80 - 70)}{(93 - 70)} = 10 / 23 = 0.44
\]

\[
a_{55} \text{(ROR)} = \frac{(10 - 8)}{(14 - 8)} = 2 / 6 = 0.33
\]

\[
a_{77} \text{(SAF)} = \frac{(3 - 2)}{(4 - 2)} = 1 / 2 = 0.50
\]

\[
a_{88} \text{(AES)} = \frac{(4 - 2)}{(4 - 2)} = 2 / 2 = 1.00
\]

2 The attribute rating matrix, as explained in section 6.2.2.1, is constructed for the power plant ‘A’ using the above calculated values of its diagonal elements (a_{ii}) and is written as:

\[
\begin{bmatrix}
1.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 \\
0.00 & 0.67 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 \\
0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 \\
0.00 & 0.00 & 0.00 & 0.44 & 0.00 & 0.00 & 0.00 & 0.00 \\
0.00 & 0.00 & 0.00 & 0.00 & 0.33 & 0.00 & 0.00 & 0.00 \\
0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 1.00 & 0.00 & 0.00 \\
0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.50 & 0.00 & 0.00 \\
0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 1.00 & 0.00
\end{bmatrix}
\]

Similarly, attribute rating matrices for each of the power plant are constructed determining the values of their diagonal elements (a_{ii}'s) using eqs. – 6.2 and 6.3.

3 The attribute matrices are constructed for each of the power plant by combining the attribute rating matrix and attribute relative importance matrix as described in section 6.2.2. The values for the elements of the attribute relative importance matrix (a_{ij}'s) are taken from the respective elements of relative importance matrix ‘D’ as given at step – 2 of section 5.6.2. The
attribute matrices, so constructed, for each of the power plant under consideration are written as:

**Power Plant – A (Attribute Matrix)**

\[
\begin{bmatrix}
1.00 & 1.25 & 0.75 & 0.25 & 1.00 & 0.75 & 1.50 & 0.50 \\
0.50 & 0.67 & 0.50 & 0.50 & 0.75 & 0.75 & 1.25 & 1.50 \\
2.00 & 4.00 & 0.00 & 1.50 & 0.50 & 0.50 & 2.25 & 0.50 \\
3.00 & 5.00 & 0.75 & 0.44 & 2.00 & 2.50 & 2.75 & 1.25 \\
1.00 & 2.00 & 3.00 & 2.00 & 0.33 & 1.25 & 0.75 & 0.25 \\
2.50 & 1.75 & 3.00 & 0.25 & 1.50 & 1.00 & 0.50 & 0.50 \\
0.25 & 1.00 & 1.25 & 0.75 & 1.75 & 3.00 & 0.50 & 0.75 \\
0.75 & 2.00 & 3.50 & 1.00 & 3.00 & 1.50 & 1.00 & 1.00 \\
\end{bmatrix}
\]

**Power Plant – B (Attribute Matrix)**

\[
\begin{bmatrix}
0.79 & 1.25 & 0.75 & 0.25 & 1.00 & 0.75 & 1.50 & 0.50 \\
0.50 & 0.53 & 0.50 & 0.50 & 0.75 & 0.75 & 1.25 & 1.50 \\
2.00 & 4.00 & 0.20 & 1.50 & 0.50 & 0.50 & 2.25 & 0.50 \\
3.00 & 5.00 & 0.75 & 1.00 & 2.00 & 2.50 & 2.75 & 1.25 \\
1.00 & 2.00 & 3.00 & 2.00 & 0.50 & 1.25 & 0.75 & 0.25 \\
2.50 & 1.75 & 3.00 & 0.25 & 1.50 & 0.86 & 0.50 & 0.50 \\
0.25 & 1.00 & 1.25 & 0.75 & 1.75 & 3.00 & 1.00 & 0.75 \\
0.75 & 2.00 & 3.50 & 1.00 & 3.00 & 1.50 & 1.00 & 0.50 \\
\end{bmatrix}
\]

**Power Plant – C (Attribute Matrix)**

\[
\begin{bmatrix}
1.00 & 1.25 & 0.75 & 0.25 & 1.00 & 0.75 & 1.50 & 0.50 \\
0.50 & 0.00 & 0.50 & 0.50 & 0.75 & 0.75 & 1.25 & 1.50 \\
2.00 & 4.00 & 0.60 & 1.50 & 0.50 & 0.50 & 2.25 & 0.50 \\
3.00 & 5.00 & 0.75 & 0.87 & 2.00 & 2.50 & 2.75 & 1.25 \\
1.00 & 2.00 & 3.00 & 2.00 & 0.75 & 1.25 & 0.75 & 0.25 \\
2.50 & 1.75 & 3.00 & 0.25 & 1.50 & 0.71 & 0.50 & 0.50 \\
0.25 & 1.00 & 1.25 & 0.75 & 1.75 & 3.00 & 1.00 & 0.75 \\
0.75 & 2.00 & 3.50 & 1.00 & 3.00 & 1.50 & 1.00 & 1.00 \\
\end{bmatrix}
\]

135
## Power Plant – D (Attribute Matrix)

$$
\begin{bmatrix}
0.00 & 1.25 & 0.75 & 0.25 & 1.00 & 0.75 & 1.50 & 0.50 \\
0.50 & 0.33 & 0.50 & 0.50 & 0.75 & 0.75 & 1.25 & 1.50 \\
2.00 & 4.00 & 1.00 & 1.50 & 0.50 & 0.50 & 2.25 & 0.50 \\
3.00 & 5.00 & 0.75 & 0.96 & 2.00 & 2.50 & 2.75 & 1.25 \\
1.00 & 2.00 & 3.00 & 2.00 & 1.00 & 1.50 & 0.75 & 0.25 \\
2.50 & 1.75 & 3.00 & 0.25 & 1.50 & 0.43 & 0.50 & 0.50 \\
0.25 & 1.00 & 1.25 & 0.75 & 1.75 & 3.00 & 0.50 & 0.75 \\
0.75 & 2.00 & 3.50 & 1.00 & 3.00 & 1.50 & 1.00 & 1.00 \\
\end{bmatrix}
$$

## Power Plant – E (Attribute Matrix)

$$
\begin{bmatrix}
0.00 & 1.25 & 0.75 & 0.25 & 1.00 & 0.75 & 1.50 & 0.50 \\
0.50 & 1.00 & 0.50 & 0.50 & 0.75 & 0.75 & 1.25 & 1.50 \\
2.00 & 4.00 & 0.00 & 1.50 & 0.50 & 0.50 & 2.25 & 0.50 \\
3.00 & 5.00 & 0.75 & 0.87 & 2.00 & 2.50 & 2.75 & 1.25 \\
1.00 & 2.00 & 3.00 & 2.00 & 0.67 & 1.25 & 0.75 & 0.25 \\
2.50 & 1.75 & 3.00 & 0.25 & 1.50 & 0.14 & 0.50 & 0.50 \\
0.25 & 1.00 & 1.25 & 0.75 & 1.75 & 3.00 & 1.00 & 0.75 \\
0.75 & 2.00 & 3.50 & 1.00 & 3.00 & 1.50 & 1.00 & 0.50 \\
\end{bmatrix}
$$

## Power Plant – I (Attribute Matrix)

$$
\begin{bmatrix}
1.00 & 1.25 & 0.75 & 0.25 & 1.00 & 0.75 & 1.50 & 0.50 \\
0.50 & 0.47 & 0.50 & 0.50 & 0.75 & 0.75 & 1.25 & 1.50 \\
2.00 & 4.00 & 0.40 & 1.50 & 0.50 & 0.50 & 2.25 & 0.50 \\
3.00 & 5.00 & 0.75 & 0.65 & 2.00 & 2.50 & 2.75 & 1.25 \\
1.00 & 2.00 & 3.00 & 2.00 & 0.17 & 1.25 & 0.75 & 0.25 \\
2.50 & 1.75 & 3.00 & 0.25 & 1.50 & 0.28 & 0.50 & 0.50 \\
0.25 & 1.00 & 1.25 & 0.75 & 1.75 & 3.00 & 0.50 & 0.75 \\
0.75 & 2.00 & 3.50 & 1.00 & 3.00 & 1.50 & 1.00 & 1.00 \\
\end{bmatrix}
$$
The suitability index for each of the power plant is calculated using the software package developed for finding the value of the attribute variable permanent function (AVPF). The power plants are ranked in the descending order of their suitability index. The ranking of the power plants in descending order along with their respective suitability index are given as below:

<table>
<thead>
<tr>
<th>Power Plant</th>
<th>C</th>
<th>B</th>
<th>E</th>
<th>A</th>
<th>I</th>
<th>D</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suitability Index</td>
<td>313170</td>
<td>293362</td>
<td>291421</td>
<td>291186</td>
<td>277875</td>
<td>269330</td>
<td>247710</td>
</tr>
<tr>
<td>Rank #</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>

This methodology is also being applied to compare the technical, economical and environmental features of various power plants. Several power plants, which could be considered for production of electricity to meet the current and future electricity demands, have been chosen. These include fossil fuel fired, nuclear and natural – renewable energy power plants. A set of criteria for optimized selection includes four major areas of concern namely energy economy, energy security, environmental and socio-economic aspects and are explained as:

**Energy Economy Aspects**

Here, energy economy is defined as cost of electricity generation. In this work, the cost of electricity generation is considered consisting of four attributes: capital cost, fuel cost, operation and maintenance cost and refurbishment cost which covers the various costs associated with plant investment and annual operation.

**Energy Security Aspects**

Commonly, the energy security aspects in electricity generation system are often expected to satisfy the existing and projected demand at a stated reliable supply.
of electricity for supporting and maintaining national development. Here, these aspects are represented by plant life, fuel supply length and foreign independency.

Environmental Aspects

No source is free from environmental impact, either direct or indirect. Use of natural resources such as land, water, pollution of air and water etc. can be considered as direct impacts, while others such as aesthetic considerations and social and habitat modifications are indirect impacts that can not easily be assessed and compared, and tend to be more subjective in their evaluation. Here various contributing attributes are: air pollution; global warming; noise level; discomfort and water requirements.

Socio – economic Aspects

Close relationship between energy in general, and electricity in particular, with the national development has been extensively discussed. The socio – economic aspects of power generation are assumed to have important affect to the selection of energy sources or energy technology includes industrial development; local participation; capacity and technology transfer. The Table – 6.2 [Widiyanto et al., 2004] shows the values of all these attributes for different power plants.

The Table – 6.3 shows the suitability index (S 1) and the ranking of the power plants based on the contributing attributes for various aspects, separately and collectively. The overall ranking is based on the value of the suitability index of each of the power plant that is determined considering all 16 contributing attributes together using AVPF as developed in section 6.2.3. The plant with highest S 1 is given rank no. – 1, that with second highest S 1 is given rank no. – 2, and so on. Here, it is assumed that all the attributes considered have equal relative importance. The results, so obtained, depict that the hydro power plant is ranked at number one based on the analysis using 16 attributes and is followed by nuclear and coal fired power plants, respectively. Further, wind power plant is found to be the best alternative plant among all non–conventional energy sources, though it is ranked at no. - 4 in overall analysis.

Where the top management is responsible for the final approval, merely mathematical figures may not suffice. Therefore, graphical techniques of Table comparison namely, histograms and graphs are also suggested. Figure – 6.3 shows the sensitivity analysis for overall suitability index of natural gas and coal fired power plants based on the manipulation of the energy economy aspects. Here, the vertical
<table>
<thead>
<tr>
<th>ASPECTS</th>
<th>ENERGY</th>
<th>ECONOMY</th>
<th>ENERGY</th>
<th>SECURITY</th>
<th>ENVIRONMENTAL</th>
<th>SOCIOECONOMIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATTRIBUTES</td>
<td>Attributes</td>
<td>Attributes</td>
<td>Attributes</td>
<td>Attributes</td>
<td>Attributes</td>
<td>Attributes</td>
</tr>
<tr>
<td>POWER PLANTS</td>
<td>Oil</td>
<td>Natural Gas</td>
<td>Coal</td>
<td>Fired</td>
<td>Geo-thermal</td>
<td>Nuclear</td>
</tr>
<tr>
<td>A1 Capital Cost [S/kWh]</td>
<td>1.6</td>
<td>1.5</td>
<td>2.2</td>
<td>3.5</td>
<td>2.6</td>
<td>2.5</td>
</tr>
<tr>
<td>A2 Fuel Cost [S/kWh]</td>
<td>2.8</td>
<td>2.7</td>
<td>2.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.8</td>
</tr>
<tr>
<td>A3 O &amp; M Cost [S/kWh]</td>
<td>0.6</td>
<td>0.5</td>
<td>1.3</td>
<td>0.3</td>
<td>0.3</td>
<td>1.6</td>
</tr>
<tr>
<td>A4 Refurbishment Cost [S/kWh]</td>
<td>0.4</td>
<td>0.3</td>
<td>0.7</td>
<td>0.4</td>
<td>0.4</td>
<td>1.6</td>
</tr>
<tr>
<td>A5 Plant Life [years]</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>10</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>A6 Fuel Supply Length [years]</td>
<td>1000</td>
<td>750</td>
<td>1000</td>
<td>750</td>
<td>1000</td>
<td>750</td>
</tr>
<tr>
<td>A7 Foreign Dependency [100]</td>
<td>90</td>
<td>75</td>
<td>60</td>
<td>40</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>A8 Air Pollution [100]</td>
<td>90</td>
<td>75</td>
<td>60</td>
<td>40</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>A9 Global Warming [gCO2/kWh]</td>
<td>1.0</td>
<td>0.9</td>
<td>0.8</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>A10 Noise Level [dBa]</td>
<td>50</td>
<td>40</td>
<td>30</td>
<td>20</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>A11 Discomfort (100)</td>
<td>40</td>
<td>30</td>
<td>30</td>
<td>20</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>A12 Water Requirement [m3/kW]</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>A13 Industrial Development [100]</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>A14 Local Participation [100]</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>A15 Capacity [MW]</td>
<td>50</td>
<td>40</td>
<td>35</td>
<td>30</td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td>A16 Technology Transfer [100]</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>
### TABLE – 6.3

**SUITABILITY INDEX AND RANKING OF POWER PLANTS**

<table>
<thead>
<tr>
<th>Energy Economy Aspects</th>
<th>Energy Security Aspects</th>
<th>Environmental Aspects</th>
<th>Socio-Economic Aspects</th>
<th>Overall</th>
<th>RANKING BASED ON</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SUITABILITY INDEX BASED ON</strong></td>
<td><strong>Energy Economy Aspects</strong></td>
<td><strong>Energy Security Aspects</strong></td>
<td><strong>Environmental Aspects</strong></td>
<td><strong>Socio-Economic Aspects</strong></td>
<td><strong>Overall</strong></td>
</tr>
<tr>
<td>Oil Fired</td>
<td>17.050</td>
<td>3.37</td>
<td>84.27</td>
<td>14.33</td>
<td>72911</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>17.589</td>
<td>3.40</td>
<td>87.76</td>
<td>15.07</td>
<td>82893</td>
</tr>
<tr>
<td>Coal Fired</td>
<td>16.068</td>
<td>4.39</td>
<td>71.06</td>
<td>17.18</td>
<td>89448</td>
</tr>
<tr>
<td>Hydro Power</td>
<td>23.616</td>
<td>6.00</td>
<td>93.50</td>
<td>15.09</td>
<td>204837</td>
</tr>
<tr>
<td>Geothermal</td>
<td>17.658</td>
<td>3.08</td>
<td>74.78</td>
<td>10.79</td>
<td>46720</td>
</tr>
<tr>
<td>Nuclear</td>
<td>17.357</td>
<td>3.24</td>
<td>84.64</td>
<td>20.33</td>
<td>100984</td>
</tr>
<tr>
<td>Solar PV</td>
<td>13.076</td>
<td>3.00</td>
<td>119.04</td>
<td>11.33</td>
<td>56691</td>
</tr>
<tr>
<td>Wind Power</td>
<td>17.320</td>
<td>3.88</td>
<td>112.72</td>
<td>11.40</td>
<td>83374</td>
</tr>
<tr>
<td>Solar Thermal</td>
<td>15.878</td>
<td>2.82</td>
<td>104.84</td>
<td>11.32</td>
<td>56807</td>
</tr>
</tbody>
</table>
SENSITIVITY TEST FOR COAL FIRED AND NATURAL GAS POWER PLANTS

FIGURE – 6.3

PERFORMANCE PROFILE OF COAL FIRED AND NUCLEAR POWER PLANTS

FIGURE – 6.4
axis represents the overall suitability index and the horizontal axis represents the percentage change in the value of the suitability index of these power plants based on energy economy aspects. The sensitivity analysis test can also be performed for the remaining power plants and the aspects in the same manner. It is found that if the suitability index for energy economy aspects that are based on cost factors is improved by ~13% for coal fired power plant then, it will be a better option than nuclear power plant. Similarly, the natural gas power plant will emerge as a better option than coal fired and nuclear power plants if its suitability index is improved by ~8% and ~23%, respectively.

In order to find the supporting factors for coal fired and nuclear power plants, a performance profile for these power plants is presented in Fig. – 6.4. This figure clearly highlights the critical and non-critical attributes and their relative comparison for both the plants. In this graph, the vertical axis gives the percentage change in the value of the suitability index of the respective aspects for a power plant corresponding to a fixed percentage change; here 10% increase, in the base value of the attributes mentioned on the horizontal axis. It is found that the attributes: operation and maintenance cost, local participation and technology transfer are the critical attributes for nuclear power plants and foreign independency, plant life and industrial development are the critical attributes for a coal fired power plant. Similarly, the attributes: foreign independency, industrial development and discomfort are non-critical attributes for a nuclear power plant and air pollution, global warming and capacity are non-critical attributes for a coal fired power plant.

Figure – 6.5, drawn using histograms, shows a summary of the results of analysis series, from which general trends of the selectivity level of each power plant can be found easily. Here, the vertical axis gives the value of the suitability index normalized on a scale of [0, 100] for various power plants corresponding to the considered aspects mentioned on the horizontal axis, separately as well as collectively. The figure is also used for comparative analysis of alternative power plants on the basis of different aspects. It is observed that hydro power plant is the most viable alternative based on energy economy and energy security aspects, whereas solar PV power plant and nuclear power plant is emerged as most viable alternatives based on environmental aspects and socio-economic aspects respectively.
GENERAL TRENDS OF SUITABILITY INDEX FOR EACH POWER PLANT

FIGURE – 6.5
6.5 COMPARISON OF MADM AND GTM METHODOLOGIES

Multiple Attribute Decision Making (MADM) and Graph Theoretical Methodology have been discussed in chapter – 5 and 6, respectively and were used to find the ranking and optimum selection of power plants based on some identified attributes of the plant. Though, the results so obtained show almost similar trends yet the graph theoretical methodology has an edge over multiple attribute decision making (MADM) methodology. The details are as under:

1. In Graph Theoretical Methodology (GTM), the maximum/minimum threshold values and maximum/minimum values of the attributes in the database are taken while constructing an attribute rating matrix whereas in Multiple Attribute Decision Making (MADM), actual values of the attributes are directly considered in the decision matrix. Also in GTM, the attributes relative importance matrix is directly used with the attributes rating matrix to construct attribute matrix and further, the permanent of this attribute matrix gives the suitability index. In MADM, the attributes relative importance matrix is used to find out the weight vector. Further, this weight vector is used for evaluation of the suitability index that is used to rank the power plants. Therefore, the computational work is rather simple and easy in GTM as compared to MADM.

2. In multiple attribute decision making methodology, it may not be possible to find the eigen values and the corresponding eigen vectors for a symmetrical matrix. The matrix will be symmetrical if the relative importance of the attributes will be interrelated i.e. either $a_{ij} = 1 - a_{ji}$ or $a_{ij} = 1/a_{ji}$. In the graph theoretical methodology, the attribute variable permanent function i.e. the permanent of the attribute matrix is used. Hence, such situations of indeterminacy of the matrix do not arise in the graph theoretical methodology.

3. A very small variation in the value of an attribute leads to a large difference in the suitability index of the plant in case of graph theoretical methodology as compared to multiple attributes decision making methodology. Therefore, it is easy to rank the power plants by graph theoretical methodology.
6.6 CONCLUSIONS

The following conclusions that can be drawn from this chapter are:

1. The Graph Theoretical Methodology (GTM) which has been developed and applied for the evaluation, ranking and optimum selection of given power plants is found to be more effective than the MADM methodology. The proposed methodology employs a relatively simple mathematical formulation and straightforward matrix operation and, thus, is capable of solving complex multi-attributes decision problems.

2. The computer software developed for GTM is a general software and is user friendly. It has been tested for a thermal power plant having 190 attributes.

3. Histograms and Graphs have been produced for identification of critical attributes, sensitivity analysis, ranking and optimum selection in order to have decisive comparison among given plants.

4. It has found easier and convincing to rank and select the power plants using GTM because it produces a large difference in the value of the suitability index of plants, with respect to a very small change in the value of the attribute.

5. The Attribute Digraph obtained using GTM is found very profound. It gives comprehensive view of all attributes and their possible interactions which are important for the selection and ranking of the power plants.

6. The conventional energy sources have emerged as the better options for electricity generation as compared to non-conventional energy sources if overall suitability of the plant is considered.

7. All the non-conventional energy systems have better position in respect of environmental aspects than the conventional sources of energy. Whereas, the conventional energy sources dominate in respect of socioeconomic aspects. However, for energy economy and energy security aspects, both types of energy systems have shown a mixed trend.

8. The sensitivity analysis test is found very useful to identify the critical and non-critical attributes as well as for exploring the influence of various different sets of attributes on overall suitability index of the plant before arriving at a final decision.