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GTA modeling of combined cycle power plant efficiency analysis

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Abstract A methodology based upon graph theory and matrix method is developed for the efficiency analysis of a Combined Cycle Power Plant (CCPP) with a view that a person at managerial level may decide regarding efficiency improvement without in-depth knowledge of conventional methods of thermal efficiency evaluation. For the analysis, CCPP is divided into six sub-systems and interdependency is identified to develop system structure digraph. Sub-system efficiencies are further dependent on numerous parameters which are interdependent. Therefore, methodology developed at system level is extended to sub-system level. Performance parameter digraph is developed at sub-system level by intriguing inheritance and interdependencies of parameters. Digraph is converted into matrix form and permanent function is developed. The value of permanent function in real time situation is compared with design condition to obtain Relative Efficiency Index (REI) at sub-system level. REI at sub-system level is guidance for deviation of efficiency index from its design value.

1. Introduction

Conversion of raw material into final product is series of energy consuming processes. Electricity is most abundantly used energy resource with highest availability. Its well-organized generation is a function of the efficiency of energy conversion system. Due to the exponential rise of electricity demand, researchers in the power plant area are hankering for best utilization of energy resources. At present there are many types of power plant e.g. steam power plant, nuclear power plant and Combined Cycle Power Plant (CCPP), etc. capable of converting chemical energy of fuel into electrical energy at large scale. For natural gas as fuel, CCPP is a promising mode of energy recovery and conservation with economically attractive scheme [1–4]. Heuristic approach for the research in thermal power plant field has amortized CCPP efficiency up to 60%. They are characterized by better thermodynamic, economical, ecological, and operating indexes. A

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Nomenclature

A/F	air fuel
C/H	Carbon to Hydrogen
CCPP	Combined Cycle Power Plant
CEI	CCPP Efficiency Index
CNG	Compressed Natural Gas
CP	Condensate Pump
DM	De-mineralized
FOD	Foreign Object Damage
FUE	Fuel Utilization Efficiency
GTA	Graph Theoretic Approach
HPH	High Pressure Heater
HRSG	Heat Recovery Steam Generator
IPT	Intermediate Pressure Turbine
LPH	low pressure heater
MADM	Multi Attribute Decision Making
PLF	Plant Load Factor
PPD	Performance Parameter Digraph
RAMS	reliability availability maintainability serviceability
REI	Relative Efficiency Index
RT	Real-Time
RTEI	Real-Time Efficiency Index
RTRI	Real Time Reliability Index
SCD	system cost digraph
SED	System Efficiency Digraph
SPP	Steam Power Plant
SSD	System Structure Digraph
SSG	System Structure Graph
TG	Turbo-Generator
TIT	Turbine Inlet Temperature
VPF-c	variable permanent system cost function
VPF-e	variable permanent system efficiency function
VPF-ep	Variable Permanent System Efficiency Parameter Function
VPSCM	Variable Permanent System Cost Matrix
VPSEM	Variable Permanent System Efficiency Matrix
VPSEPM	Variable Permanent System Efficiency Permanent Matrix

CCPP is a combination of CNG fired turbine as topping cycle and a steam powered turbine as bottoming cycle with Heat Recovery Steam Generator (HRSG) as mean of recovering waste heat from gas turbine and transferring to steam turbine. CCPP is humongous (typically rated in the hundreds of megawatts), multifaceted and intricate structure.

As part of its by and large stratagem for reforms in the electricity sector, the government plans to expand the installed capacity of combined cycle thermal power stations, given adequate gas reserves in the country. In this context, it becomes imperative to assess the performance, reliability and efficiency of combined cycle thermal power plants in India. A power plant is considered inefficient if the plant's existing resources or inputs are utilized sub-optimally, as a consequence of which the plant's power generation is less than its potential or maximum possible generation. Efficiency, to effectively utilize the energy supplied, is influenced by the design, manufacturing, construction, operation, and maintenance of subsystems and equipments of power plant. Capability and efficiency reflect how well the power plant is designed and constructed [5]. In general, technical inefficiency is indicative of poor plant performance, while an improvement in plant efficiency or Technical Efficiency (TE) leads to higher electricity generation given existing inputs and hence superior plant performance [6].

It is the nature of power plants that they do not work at all times at their design point conditions due to degradation and aging of plant equipments and components [7]. Off-design due to normal conditions (change of ambient conditions and part load) and abnormal conditions (change in fluid path component configuration due to degradation) are two main sources which offset the plant from its design point conditions. Therefore, power plant efficiency has to be calculated by taking these conditions into consideration. But CCPP is a very large and complex system and performance of its components and systems are closely intertwined and insuperable without taking the effect of others. Such as the performance of steam turbine not only depends upon steam turbine efficiency but it is also affected by other systems such as Heat Recovery Steam Generator (HRSG) and water system. Therefore, design of CCPP, improvement in existing plant and comparison of two real life operating power plants requisite a Multi Attribute Decision Making (MADM) technique to analyze the effect of one system/design parameter on the other systems/design parameters. Many MADM techniques are on hand in literature and Graph Theoretic Approach (GTA), one of them, is found to be suitable for the present analysis. Methodology based upon GTA is easy to develop because outcome may be had in three steps i.e. digraph development, matrix development and permanent function development. Permanent function developed may be calculated with the help of computer programming tool. Computational time is also very less. Once a GTA model is developed for CCPP efficiency analysis then it may be used even if number of subsystems and parameters are increased or decreased.

As decision making GTA has been used in the field of mechanical engineering for mechanisms and machine theory, computer aided design, robotics, and manufacturing, etc. [8–10]. Mohan et al. [11] developed GTA based methodology to evaluate the performance of a Steam Power Plant (SPP). For the analysis of SPP, boiler system was modeled with structural interconnection with other subsystems. A detailed methodology was described for developing a System Structure Graph (SSG), various system structure matrices, and their permanent functions. But in this work no quantitative data were reported for the analysis. Results were in the form of an index which is qualitative indication of its performance. The methodology developed in this work was extended to develop a mathematical model for determining the maintenance criticality index for the equipment of a coal-based steam power plant [12]. The maintainability model developed in this work can be used for deciding an appropriate maintenance strategy for any type of coal based power plant while in operation. Wani and Gandhi [13] developed GTA based methodology for the studying the importance of maintainability attributes at design stage.

Mohan et al. [14] applied GTA to calculate Real-Time Efficiency Index (RTEI) for a steam power plant which is the ratio of the values of variable permanent system structure function called as VPF in Real-Time (RT) situation to its achievable design value. The proposed methodology was explained with the help of two examples and both were for the SPP in operating stage. The efficiency calculation was mainly based upon the heat transfer process. Garg et al. [15] developed graph theoretical methodology to compare various technical and economical features of wind, hydro and thermal power plants. Suitability factor for three plants (a) Thermal Power Plant (b) Hydro Power Plant (c) Wind Power Plant, was calculated based on installation cost, cost of electricity generation and Plant Load Factor (PLF). Thermal power plant was found to be most suitable and after that was Hydro power plant followed by Wind power plant.

Mohan et al. [16] obtained Real Time Reliability Index (RTRI) for a SPP using GTA. Salient features of GTA that incorporation or deletion of any number of systems and subsystems, consideration of interaction among subsystems were also discussed. It was also pointed out that the methodology developed can be applied for obtaining other RAMS (Reliability, Availability, Maintainability, Serviceability) indices: availability and maintainability; including optimum selection, bench marking, and sensitivity analysis of a SPP.

In the literature graph theoretic methodology is explained in detail for the decision making in different situations. But during literature survey authors did not come across any work, calculating the efficiency of a CCPP with the help of GTA. In this work a methodology using GTA is developed that enables the prediction of the efficiency of a CCPP in terms of an index by taking into account various design parameters and interactions between them.

2. Graph Theoretic Analysis (GTA)

Research in engineering and science is initiated with system modeling and analyzing it with the help of some mathematical equations and computing tools. For the GTA system is modeled in the form of nodes and edges. Nodes represent the subsystem or any attribute. Directed edge from one node to another is to give an idea about interdependency of a subsystem or attribute on the other. This combination of nodes and edges is called System Structure Digraph (SSD). SSD can be developed for any of the performance attributes e.g. efficiency, reliability, maintainability etc. For the computational analysis SSD is converted into matrix form. Adjacency matrix, characteristic structural features matrix, characteristic system structure matrix, variable characteristic system structure matrix and variable permanent system structure matrix are five steps to develop matrix form of the SSD [17,18]. Variable permanent system structure matrix is expanded and all the negative signs in the determinant are replaced with positive sign to retain structural information of the system. The determinant obtained in this way is called as variable permanent system structure function. The value of the permanent function is calculated with the computer programming tool developed in language C^{++}.

Thermodynamic efficiency of a CCPP is dependent on the efficiency of subsystems and efficiency of interconnections. If the plant is operating at the design conditions then it is expected that its efficiency is maximum. At off-design conditions efficiency is effected by design and operating parameters. For GTA system modeling is carried at system level by taking the efficiency of subsystems and their interconnections. Afterward modeling is extended to sub-system level to study the effects of design and operating parameters by GTA. Inheritance and interdependencies of the parameters is also taken into consideration. In the next section working of CCPP is explained and system structure graph is developed.

3. CCPP system structure

CCPP, considered for the present analysis, is shown in Fig. 1. The air at the ambient temperature and pressure enters the air compressor after being filtered by air filters. Mechanical energy of compressor is used to compress the air so that higher quantity of fuel may be added in air at lesser volume in combustion chamber. After compression air comes to combustion chamber and mixes with the Compressed Natural Gas (CNG) from the fuel supply system. Activation energy for the reaction between air and fuel is being provided by spark between two electrodes and reaction is at constant pressure. After this, hot combustion gases enter the gas turbine where thermal energy of flue gases is converted into mechanical power of gas turbines. HRSG is the link between the gas turbine and the steam turbine process, whose function is to transfer heat energy from exhaust gases to pressurized water and produces superheated steam. The steam is separated in the boiler drum and supplied to the super heater section. The super heated steam produced in the super heater then enters into the steam turbine through the turbine stop valve. After expansion in steam turbine the exhaust steam is condensed in the condenser. In the cooling water system, heat of steam turbine exhaust is carried away by the circulating water, which is finally rejected to the atmosphere with the help of cooling towers. Because of this direct path to the atmosphere, surrounding water bodies typically do not suffer adverse thermal effects [19]. The power plant is a series of systems except for the cooling tower that is modeled as K out of N systems, meaning that it is necessary to have a given number of cooling towers working (K) out of total N to allow the plant to achieve nominal output [5]. The abridged model as explained above is easy to analyze with GTA.

4. Graph Theoretic Analysis of CCPP

System structure development is the input for deliberation and examination of system performance analysis [20]. System structure either physical or abstract is chosen corresponding to the methodology of analysis and parameters to be evaluated. The physical structure of a system involves subsystems, assemblies, components and their interconnections, while performance or failure contributing events are represented in abstract structure.

A real life CCPP system is highly complex due to large number of interdependent components and parameters. Complexity of system analysis is eased if system is divided into subsystems and sub-divisions are decided corresponding to the method of analysis. In the present analysis air, flue gas, steam, water and fuel flow are physical phenomena which affect work and heat transfer during the cycle of processes. Efficiency of

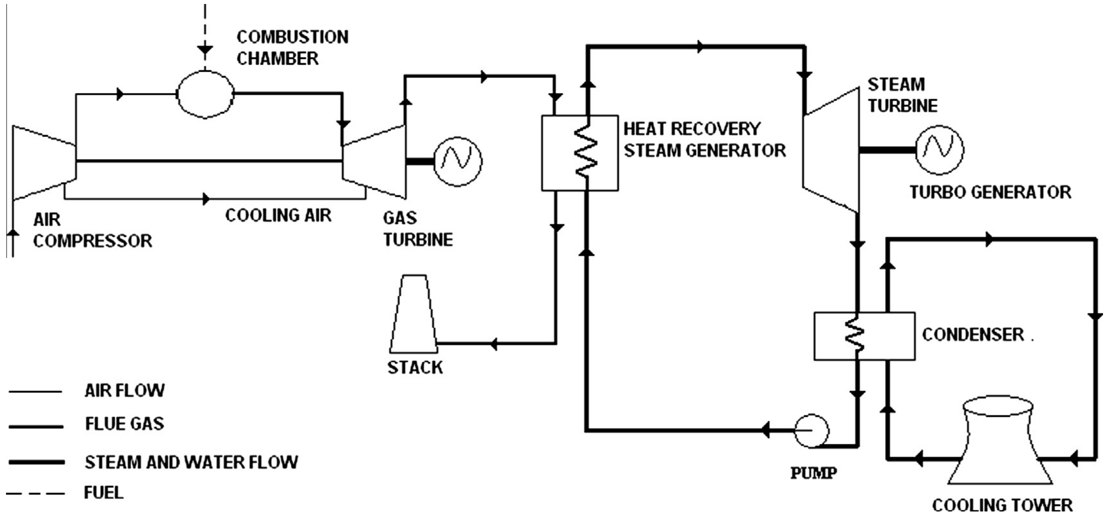

Figure 1 Schematic flow diagram of combined cycle power plant.

work and heat transfer capacity of components is pullback from isentropic efficiency of the plant. Besides laws of thermodynamics many design and operating parameters are also responsible for this. Keeping in mind the inheritance and interdependencies of components and parameters, CCPP is divided into following six subsystems:

1. Air Compressor System (S_1).
2. Combustion Chamber System (S_2).
3. Gas Turbine System (S_3).
4. Heat Recovery Steam Generator System (S_4).
5. Steam Turbine System (S_5).
6. Water System (S_6).

As subsystems are also very large, therefore it is appropriate to refer them also as system. Here, air system is considered a part of air compressor system and fuel system is a part of combustion chamber system. In a CCPP, gas turbine and steam turbine may be installed either on same shaft or on separate shaft. In the present analysis turbo-generators are attached with gas and steam turbine and considered to be a part of them.

Partitioning of combined cycle power plant in six systems is founded on the functioning of singular components with possibility of partitioning further into sub-subsystems. Let each of the six systems of plant be represented by vertices S_i's ($i = 1, 2, 3, 4, 5, 6$) and interconnection between two systems (S_i, S_j) is represented by edges c_{ij}'s ($i, j = 1, 2, 3, 4, 5, 6$ and $i \neq j$) connecting the two vertices S_i and S_j. In the combined cycle power plant all these six systems are connected by flow of air, flue gases, water, steam, heat and work. This flow is shown in Fig. 2 with the help of vertex and edges. This representation is called as System Structure Graph (SSG). This is based upon the functioning of combined cycle power plant as per the following:

1. The ambient air comes to the compressor after being filtered by air filters. Compressor and turbine are attached with a rigid shaft. Therefore, the power to compress the air comes to the compressor from the turbine. This is represented by the edge c_{31}. S_1 and S_3 are the air compressor and gas turbine system respectively.

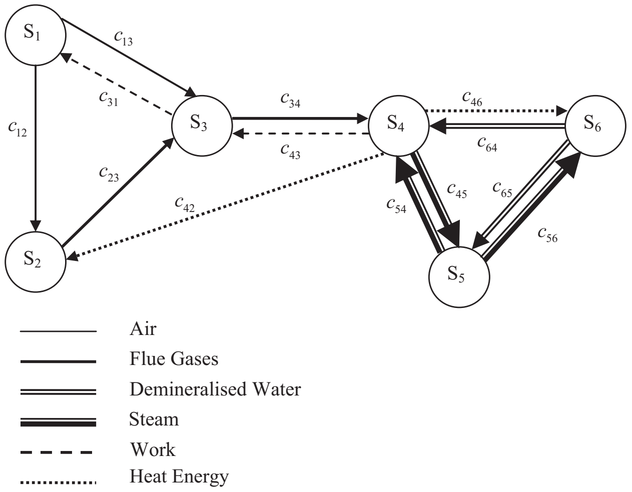

Figure 2 System structural graph of CCPP with material and energy interaction.

2. After compression, air goes to the combustion chamber. This is represented by edge c_{12}. Fuel is added in the combustion chamber.
3. A blade is cooled by being made hollow so that a coolant air can circulate through it. Coolant air is obtained directly from the compressor, thus, bypassing the combustion chamber. Edge c_{13} represents the bypassing of cooling air.
4. Fuel supplied to the combustion chamber is generally CNG. Fuel supply is taken as a part of combustion chamber system. Outlet temperature of combustion chamber system [S_2] is fixed corresponding to thermal stress limit of gas turbine blade material. Highest temperature of flue gas coming out from combustion chamber is controlled by changing air–fuel (A/F) ratio. Combustion product flows to gas turbine as shown by edge c_{23}.
5. Depending upon the temperature of flue gas, HRSG [S_4] may be used for (i) partial heating (regeneration) of the compressed air leaving the compressor (c_{42}), (ii) feed

water heating of the steam cycle in a closed type feed water heater (c_{46}), or (iii) generating steam in a dual or multipressure steam cycle.

6. Flue gas coming out of combustion chamber and entering to HRSG system [S_4] are shown by the edge c_{34}.
7. Due to HRSG [S_4] heat transfer surfaces fouling, back-pressure is increased and the gas turbine [S_3] does not work at its design point condition because of the inherent problems which accompanies the increase of back-pressure, e.g., high torque on the shaft, coupling forces on thrust bearing, and vibration [7]. It is shown by the edge c_{43}.
8. High temperature and high pressure steam flows from HRSG system to steam turbine system [S_5] as shown by edge c_{45}.
9. Single stage reheating is employed between High Pressure Turbine (HPT) and Intermediate Pressure Turbine (IPT). For this steam coming out from HPT [S_5] is sent to HRSG [S_4] shown by edge c_{54}.
10. From steam turbine, low pressure and low temperature steam comes to the cooling tower (c_{56}) and after condensation it goes to HRSG after passing through the pump.
11. De-mineralized (DM) feed water is injected to control the temperature of superheated and reheated steam as an attemperation spray (c_{65}).
12. DM water from the water circuit [S_6] is fed to HRSG as feed water represented by edge c_{64}.

The SSG of Fig. 2 represents different systems and their interconnections as discussed above. This graphical representation lets the incorporation or omission of any interconnection or system in order to make it closer to a real life combined cycle power plant based on different design and principles in any given situation. SSG is simplified for the analysis and all the directed edges are shown by same type arrow headed lines. As the system structure graph generated in this way is having directed edges, therefore, it will be called as System Structure Digraph (SSD). SSD corresponding to the SSG of Fig. 2 is shown in Fig. 3.

4.1. System Efficiency Digraph (SED)

System structure digraph for the power plant as shown in Fig. 3 is developed with a view that it suitably represents systems and their interactions. If efficiency of any system is changed then inheritance of system and efficiency of interconnection is also changed. The behavior of system interaction, in case of efficiency will also remain same. Therefore, SSD developed in Fig. 3 can be converted into System Efficiency Digraph (SED) by assigning notions to the nodes and edges. Let efficiency of the six systems of plant be represented by vertices D_i's (i = 1, 2, 3, 4, 5, 6) and interconnection between two systems (D_i, D_j) is represented by edges d_{ij} (i, j = 1, 2, 3, 4, 5, 6 and $i \neq j$) connecting the two vertices D_i and D_j. Then SED developed corresponding to Fig. 3 will be as shown in Fig. 4.

4.2. Variable Permanent System Efficiency Matrix (VPSEM)

The procedure for converting a SED into variable permanent matrix is similar to the methodology developed for performance analysis and may be seen somewhere else [18]. The matrix corresponding to the SED of Fig. 4 is called as Variable Permanent System Efficiency Matrix (VPSEM) Z_c and is written as in expression (1). The matrix representation gives an overview of the systems and interdependencies of the systems. In VPSEM, inheritance of systems is shown by diagonal elements and non-diagonal elements are for interdependency of systems. If any edge is absent in SED then it is assigned as zero. Inheritances and interdependencies of six systems are different and change in any value will affect the other elements also. Therefore, matrix representation is suitable for index development. Systems are dependent on each other either directly or indirectly. Increase or decrease in efficiency of systems or interdependency will affect the efficiency of systems to which it is connected directly. These systems are further connected with other systems. Therefore, they are also affected but indirectly. In actual life operating power plant, some sophisticated controls and actuations are provided so that off-design condition's outcome of one system on other systems can be minimized. But still it is impossible to filter the effect of

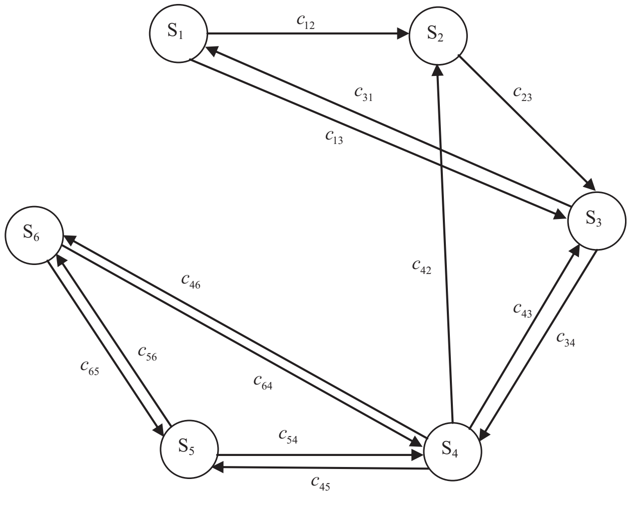

Figure 3 Digraph showing six systems (S_i) of CCPP and their interdependencies (c_{ij}).

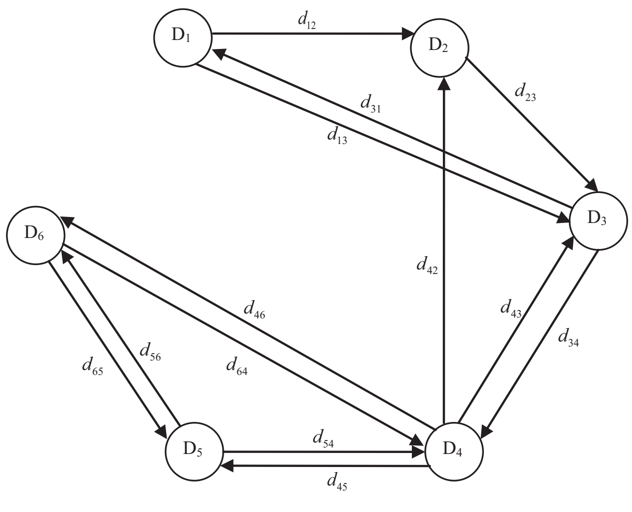

Figure 4 Digraph showing six attributes of CCPP and their interdependencies.

one system inefficiency on the other. VPSEM is dependent upon SED. A digraph cannot be quantified for computing the results. VPSEM is the bridge in-between variable permanent system efficiency function and SED. The functional form is easy to analyze with the help of computing tool after quantification.

$$Z_c = \begin{bmatrix} D_1 & d_{12} & d_{13} & 0 & 0 & 0 \\ 0 & D_2 & d_{23} & 0 & 0 & 0 \\ d_{31} & 0 & D_3 & d_{34} & 0 & 0 \\ 0 & d_{42} & d_{43} & D_4 & d_{45} & d_{46} \\ 0 & 0 & 0 & d_{54} & D_5 & d_{56} \\ 0 & 0 & 0 & d_{64} & d_{65} & D_6 \end{bmatrix} \tag{1}$$

4.3. Variable permanent system efficiency function

The permanent function of VPSEM is called the variable permanent system efficiency function and is abbreviated as VPF-e. VPF-e for matrix (1) is written as:

$$\begin{aligned} Det[Z_c] = {} & [(D_1D_2D_3D_4D_5D_6) + (d_{13}d_{31})(D_2D_4D_5D_6) \\ & + (d_{34}d_{43})(D_1D_2D_5D_6) + (d_{45}d_{54})(D_1D_2D_3D_6) \\ & + (d_{46}d_{64})(D_1D_2D_3D_5) + (d_{56}d_{65})(D_1D_2D_3D_4) \\ & + (d_{45}d_{56}d_{64})(D_1D_2D_3) + (d_{46}d_{65}d_{54})(D_1D_2D_3) \\ & + (d_{23}d_{34}d_{42})(D_1D_5D_6) + (d_{12}d_{23}d_{31})(D_4D_5D_6) \\ & + (d_{34}d_{43})(d_{56}d_{65})(D_1D_2) + (d_{13}d_{31})(d_{56}d_{65}) \\ & \times (D_2D_4) + (d_{13}d_{31})(d_{46}d_{64})(D_2D_5) + (d_{13}d_{31}) \\ & \times (d_{45}d_{54})(D_2D_6) + (d_{23}d_{34}d_{42})(d_{56}d_{65})D_1 \\ & + (d_{45}d_{56}d_{64})(d_{13}d_{31})D_2 + (d_{46}d_{65}d_{54})(d_{13}d_{31})D_2 \\ & + (d_{12}d_{23}d_{31})(d_{56}d_{65})D_4 + (d_{12}d_{23}d_{31})(d_{46}d_{64})D_5 \\ & + (d_{12}d_{23}d_{31})(d_{45}d_{54})D_6 + (d_{12}d_{23}d_{31})(d_{45}d_{56}d_{64}) \\ & + (d_{12}d_{23}d_{31})(d_{46}d_{65}d_{54}) \end{aligned} \tag{2}$$

The quantified values of D_i and d_{ij} in the expression (2) results in the form of an index called as CCPP Efficiency Index (CEI) in the present case. The main features of CEI are as follows:

1. This index is quantitative representation of CCPP efficiency and a mean to evaluate the effect of six systems efficiency and interdependency on combined cycle power plant efficiency.
2. By changing the value of inheritance (D_i) and interdependency (d_{ij}), index value is changed. A comparison in between the index values for different D_i and d_{ij} is helpful to study the effect or importance of different systems.
3. Index value may be used for the comparison of combined cycle power plant efficiency under varying sets of inheritance of systems.
4. Efficiency of two or more power plants may be compared on design or performance basis and it may help in deciding selection criteria for the new plant or improvements for the existing one may be suggested.

Every term in the permanent function carries information about the physical systems of combined cycle power plant. Permanent function developed above for the efficiency index may also be written by visual inspection of SED in Fig. 4. In SED there are five two system efficiency loops $\{(d_{13}d_{31}), (d_{34}d_{43}), (d_{45}d_{54}), (d_{46}d_{64})$ and $(d_{56}d_{65})\}$, four three system efficiency loops $\{(d_{12}d_{23}d_{31}), (d_{23}d_{34}d_{42}), (d_{45}d_{56}d_{64})$ and $(d_{46}d_{65}d_{54})\}$. There is no loop with four, five or six system efficiency. All the possible combinations with these loops covering all the systems are shown in expression (2). The details of terms for a six attribute digraph are expressed in Fig. 5.

The value of the permanent function is calculated with the help of computer programming tool. For calculation of permanent function, values of the interdependencies (d_{ij}) and inheritance (D_i) have to be quantified in the expression (2). For a thermal system, isentropic efficiency is the maximum efficiency. Therefore, it may be considered as benchmarking process and in real life situation every system is performing below isentropic efficiency. Based on the practical data available, quantitative values are assigned to system inheritance and interdependencies. The value of D_i called as inheritance can be assigned from 1–9 based on the level of real life performance of the six systems as shown in Table 1. Similarly, the value of d_{ij} (interdependency) between the two systems or parameters can be assigned a value on a scale of 1–5 as mentioned in Table 2 based on the strength of interdependency expected in the real life situation.

If the system is performing isentropic then its inheritance is 9. When it is performing its worst then it is assigned a value of 1. All the other values in the Table 1 are relative and their selection decision is based upon the judgement of personal from the industry or academia. Scales for D_i and d_{ij} may and may not be in the similar order. In the present work, for the demonstration of the proposed methodology, value for d_{ij} is taken in-between 1 and 5. If the efficiency of a system is highly reliant on the other system then corresponding d_{ij} is 5. If the interdependency of system efficiency on the other systems is very weak then corresponding d_{ij} is 1. In-between these two extremes other values are relatively compared values.

It is worth to mention that any scale for D_i or d_{ij} can be selected and the final ranking is not affected as these are relative values [13,21,22]. However, lower scale value is desirable to obtain a manageable value of performance index and also to reduce partisanship.

In real life situation inheritance of the six systems is further dependent on the design parameters. Design parameters not only affect the efficiency of systems but each other also. This makes the efficiency analysis highly complex. Effect of design parameters on systems efficiency are studied using digraph and matrix method at system level. Performance Parameter Digraph (PPD) is developed at system level which takes care of inheritance and interdependency of design parameters affecting the efficiency of that system. For the simplification of analysis and to obtain the manageable value of efficiency index the concept of Relative Efficiency Index (REI) is used. The first step for the efficiency analysis at system level is to identify the design parameters, corresponding to each system, affecting its efficiency.

5. Identification of design parameters for CCPP system

The design parameters affecting CCPP performance are very large in number. It is difficult to establish relationship among these design parameters without categorizing them in relation

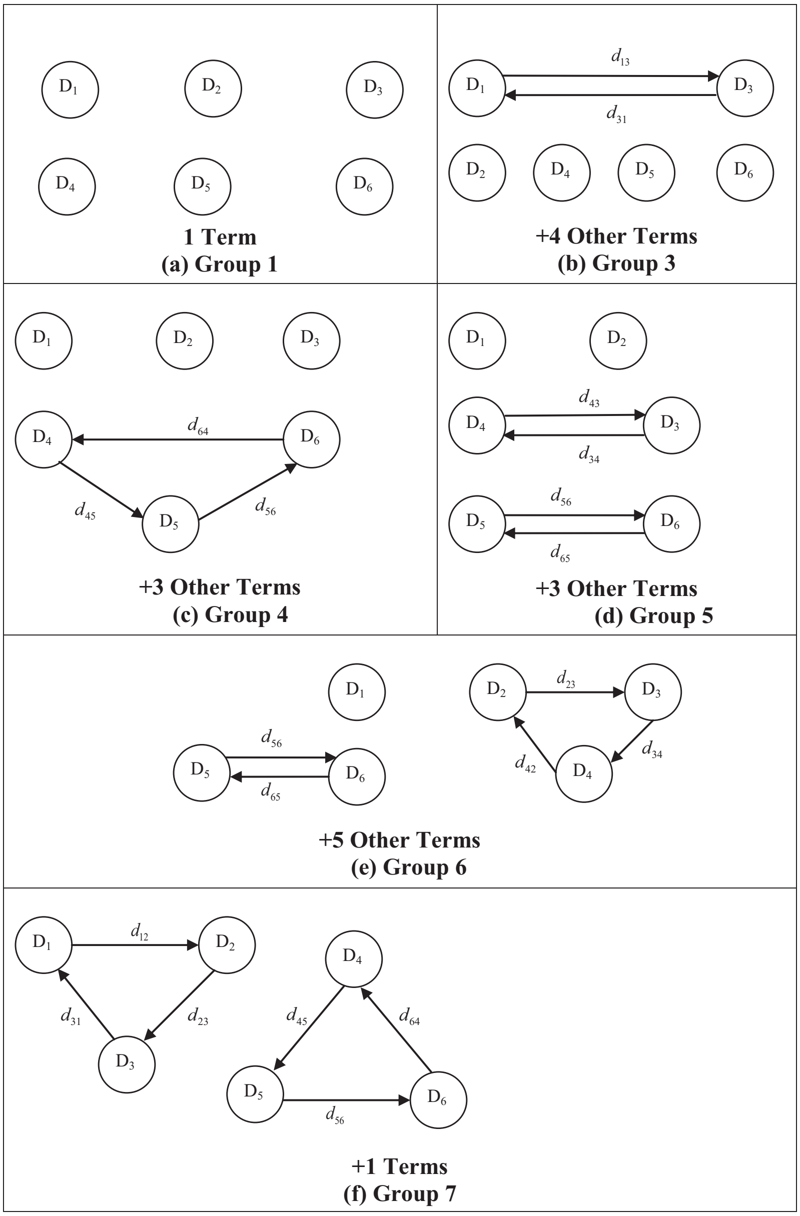

Figure 5 Graphical representation of permanent function (Eq. (2)) corresponds to digraph in Fig. 4.

Table 1 Quantification of systems or parameters affecting CCPP performance.

S. no.	Qualitative measure of parameters affecting performance	Assigned value of parameter (inheritance)
1	Exceptionally low	1
2	Very low	2
3	Low	3
4	Below average	4
5	Average	5
6	Above average	6
7	High	7
8	Very high	8
9	Exceptionally high	9

to six systems. The design parameters affecting the CCPP efficiency have been identified based on the literature survey and industrial data. The digraph at system level, is developed to represent the inheritance and interdependencies of design parameters. The parameters identified are epitomized in Fig. 6 corresponding to each system.

Rationales for selecting the design parameters for air compressor, combustion chamber, gas turbine, HRSG, steam turbine and water system are discussed below.

5.1. Compressor system

Axial flow compressor is used to compress filtered air before entering combustion chamber. The thermodynamic losses in compressor are incorporated in the model by considering polytropic efficiency in place of isentropic efficiency. The main gas path components of the gas turbine cycle, namely compressor and turbine, will degrade with engine use, which then results into engine performance deterioration [22–25]. Design

Table 2 Quantification of interdependencies/off diagonal elements.

S. no.	Qualitative measure of interdependencies	Assigned value of interdependencies
1	Very strong	5
2	Strong	4
3	Medium	3
4	Weak	2
5	Very weak	1

parameters affecting air compressor system efficiency are as explained below:

1. For compressing the air at a higher temperature; the compressor needs a more significant work. With the increase of the ambient temperature, the compressor work is increased and the net power output is decreased, which affect in decreasing the thermal efficiency [26,27]. Output of CCPP is a strong function of the inlet air temperature. When the inlet air temperature drops, cycle power output increases considerably and heat rate varies slightly [28]. Where heat rate is heat input required to produce a unit quantity of power.
2. Enthalpy and specific heats (both at constant pressure and constant volume) for a gas at particular temperature and pressure have different values for humidified air and non-humidified air. This difference depends upon the relative humidity [29].
3. Compressor efficiency is a function of manufacturing quality. Different gas turbine has different efficiencies [30,31]. Compressor erosion is represented by a lower inlet mass flow capacity and a reduction in compressor isentropic efficiency [23].
4. Due to fluid friction, pressure ratio across the compressor would be greater than the pressure ratio across the turbine. The thermal efficiency of ideal Brayton Cycle is being given by the following relationship

$$\eta_{TH} = 1 - \frac{1}{r_p^{\frac{(\gamma-1)}{\gamma}}} \tag{3}$$

   r_p is the compressor pressure ratio, and γ is the ratio of specific heats.
5. Compressor outlet temperature is the temperature at which compressed air will be entering the combustor. It is affected by the pressure ratio and polytropic efficiency of compressor.

5.2. Combustion chamber system

Combustion chamber system includes the consideration of losses due to incomplete combustion and pressure loss due to friction. Loss due to incomplete combustion is taken care by the use of the concept of combustion efficiency, while pressure

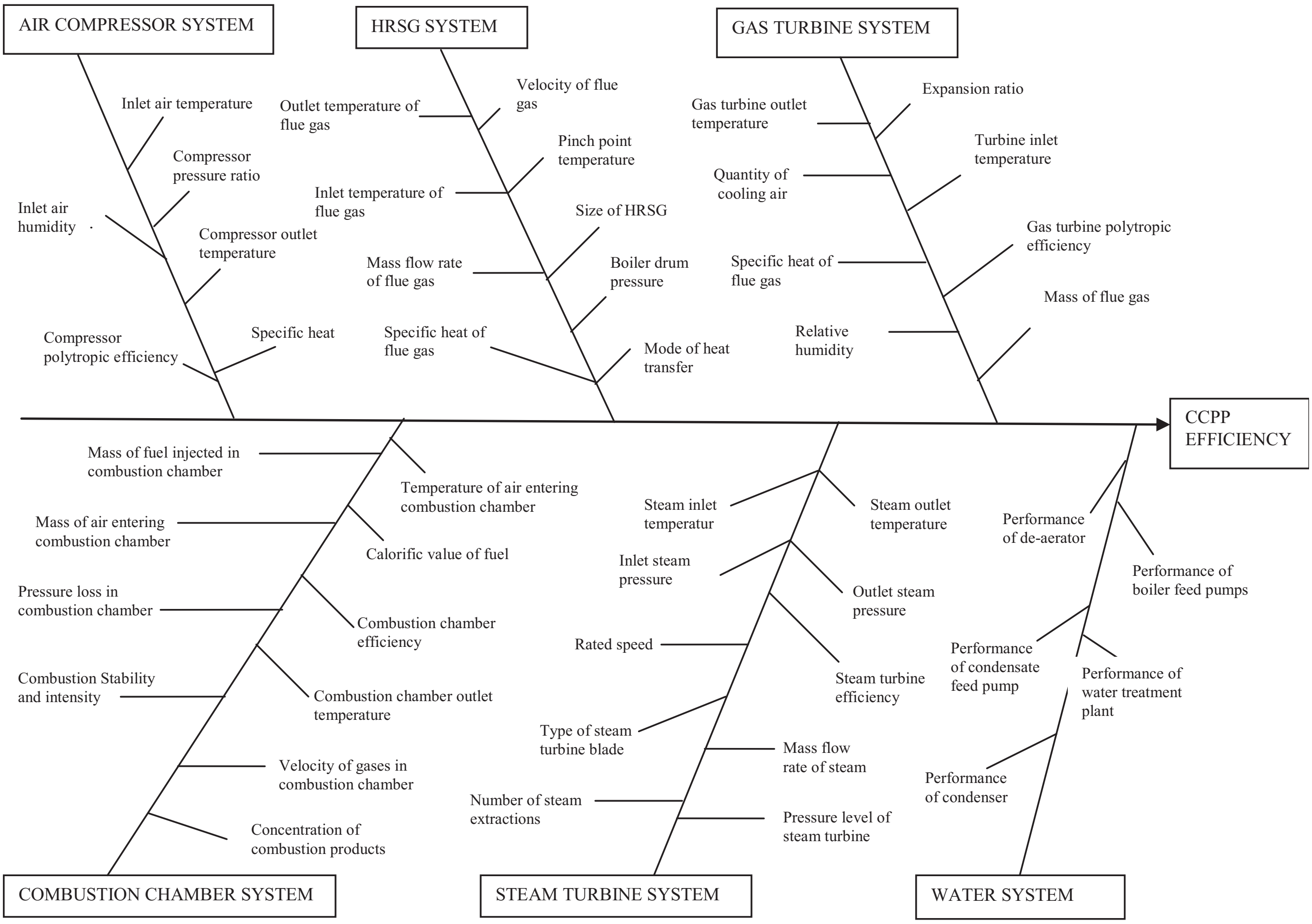

Figure 6 Diagram showing systems of CCPP and design parameters.

loss is accounted by taking percentage pressure drop of the combustor inlet pressure. Rationales for selecting the combustion chamber design parameters are as given below:

1. If the inlet temperature of air to combustion chamber is higher than lower amount of fuel is required to attain the combustion outlet temperature or Turbine Inlet Temperature (TIT).
2. Type of fuel used in combustion chamber is one of the deciding factors that how much heat is released by burning unit amount of fuel. Ratio of Carbon to Hydrogen (C/H) decides the calorific value of fuel. With the increase in fuel-calorific value the burning velocity increases which decline the NOx conversion rate slightly [32].
3. Combustion chamber loses energy due to heat transfer, noise and vibration. Fuel Utilization Efficiency (FUE) depends upon the design of combustion chamber. FUE of a plant is the ratio of all useful energy (power and process heat) extracted from the system to the input fuel energy [19].
4. Overall efficiency of cycle depends upon the amount of fuel injected in combustion chamber being other factors same. There is no other supply of energy to the cycle for a fixed net output power, so mass of fuel injected will be deciding factor for cycle efficiency.
5. If the mass of air entering the combustion chamber gets changed and amount of fuel is unchanged then combustion chamber outlet temperature will depend upon the mass of air. For a lean fuel–air mixture, if amount of fuel remains same and mass of air decreases then temperature of flue gas is increased.
6. Combustion chamber outlet temperature is fixed by thermal stress limit of turbine blade material. As the TIT changes the cycle efficiency also changes.
7. Under high pressure conditions, combustion efficiency improves with increase in pressure in combustion chamber [33].

5.3. Gas turbine system

Each row of the turbine is treated as an expander whose walls continuously extract work. Expansion process in turbine is polytropic and the polytropic efficiency takes care of losses in the expansion process. Performance deterioration in gas turbines is due to fouling, increase in tip clearance, water ingestion and Foreign Object Damage (FOD) [23]. Design parameters affecting gas turbine system efficiency are based upon the following reasoning:

1. Expansion ratio of gas turbine and compression ratio of compressor are mutually dependent. Increase in expansion ratio along with turbine inlet temperature decreases specific fuel consumption and in return efficiency is increased [1,34,35].
2. In principle, raising the turbine inlet temperature increases the efficiency and the specific work output of gas turbine cycles [3].
3. If the efficiency of gas turbine is higher then the utilization of energy in gas turbine is higher. Turbine erosion is represented by an increased flow capacity plus a reduction in the turbine isentropic efficiency [23].
4. Flue gases coming out of gas turbine at lower pressure and high temperature are passed through HRSG for waste heat recovery.
5. Cooling air is passed through the blades for cooling [36]. This air quantity is fixed by air-by-pass ratio.

5.4. Heat Recovery Steam Generator (HRSG) system

In the case of the HRSG and the condenser (heat exchangers), two types of degradation are available, one is the outer tubes surface fouling and corrosion due to flue gas, and another is the inner tubes surface scaling or erosion due to impurities dissolved in water. Even with the latest fuel treatment techniques, the exhaust gases from the gas turbine contain some chemicals in the form of soot which deposits on the outer heat transfer surfaces of the HRSG. The impurities present in circulating water deposit on the inner walls of the heat exchanger pipes and lead to reduction in the heat exchanger performance (effectiveness). Nine design parameters are identified affecting HRSG efficiency based upon the following explanations:

1. It is being found that introducing multipressure steam generation in the HRSG in place of single pressure improves the performance of CCPP. HRSGs are classified into single, dual, and triple pressure types depending on the number of drums in the boiler [37].
2. Due to increased velocity of flue gas, convective heat transfer coefficient of flue gas is increased. If the velocity of flue gases coming of gas turbine is high then more heat is transferred to HRSG tubes and steam is produced at high temperature and pressure [38].
3. Heat transfer by conduction mode is more than convection mode for the same temperature difference. Heat transfer by radiation is very less in case of flue gas.
4. If the flue gas is having high specific heat then there will be very less drop in temperature of flue gases while passing through HRSG for a specific amount of heat transfer [39].
5. A large size of HRSG will minimize the heat loss but this will increase the cost of construction [37].
6. Temperature of gases coming out from HRSG is being limited by the dew point temperature of flue gases [40,41]. At lower temperature, water present in flue gas is condensed and leads to the corrosion of stack walls due to reaction in between water and SO_2 present in flue gas. Higher flue gas temperature leads to increased energy lost to the environment and drop in efficiency.
7. The HRSG steam production for a given gas turbine goes down as the steam pressure and temperature goes up [42,43].
8. The amount of steam generated in the HRSG depends on the pinch point of the boiler [43–45]. Where pinch point is the difference between gas temperature leaving an evaporating section and the temperature at which boiling occurs.

5.5. Steam turbine system

A steam turbine is a mechanical device that extracts thermal energy from pressurized steam and converts it into a useful mechanical work. Steam turbine is attached with the Turbo-Generator (TG) and mechanical energy obtained from steam turbine is used for electricity generation. The high pressure section of a steam turbine is a single stage flow turbine and low pressure section is double flow type. As with the case of gas turbine gas path components, the steam turbine cycle steam path components are also subjected to degradation due to fouling, erosion and corrosion [7]. Design parameters selected for steam turbine are due to following reasons:

1. Pressure ratio across steam turbine depends upon water pressure in HRSG. Higher pressure ratio leads to higher efficiency.
2. Steam turbine has some internal losses due to which efficiency of cycle decreases. Higher steam turbine efficiency means higher CCPP efficiency.
3. Turbine work per unit pressure drop is much greater at the low pressure end than at high pressure end of a turbine [46]. In a condenser by lowering the back pressure, steam flow for a given output reduces and thus the plant efficiency increases.
4. Inlet temperature of steam in steam turbine is fixed by thermal stress limit of blade material. Lowering the temperature leads to lower efficiency.
5. Steam turbine exhaust pressure is equal to the saturation pressure corresponding to the condensing steam temperature, which in turn, is a function of cooling water temperature [47].

5.6. Water system

Demineralised water is required for cooling the equipments. A plate heat exchanger is installed between equipment cooling water system and auxiliary cooling water system to exchange heat between demineralised water and auxiliary cooling water. Equipment Cooling Water (ECW) system supplies demineralised cooling water to air compressor cooler, high pressure feed pump cooler, steam turbine lubricating oil cooler, steam turbine generator cooler and condensate extraction pump thrust bearing cooling system. The inefficiency of condenser is due to pressure and heat losses and causes undercooling of the condensate. Inefficiency of water system is associated with its equipment's inefficiency which is due to the reasons as explained below:

1. Clarification of raw water and preparation of demineralized (DM) water is accomplished in the DM plant and supplied to the deaerator [4].
2. In the CCPP cooling water is utilized to condense the steam discharged from the steam turbine [31]. Steam condensate and DM make-up water passes to the deaerator through low-pressure heaters (LPHs) with the help of Condensate Pumps (CP). Large size of condenser gives better effectiveness but cost of the system increases.
3. Condensed water from the condenser, with the help of the boiler feed pump (BFP), passes through High Pressure Heaters (HPH) and the economizer to boiler drum. Some part of energy is lost in the pumps.
4. Some part of energy is lost in boiler makeup water system.
5. From the cooling towers some part of energy is lost to the environment and this depends upon the back pressure of steam at steam turbine outlet.

Factors identified and quantified are interdependent and performance parameter digraph representation is suitable for visual inspection. As category and amount of factors for each system are dissimilar, so are the digraphs. Methodology for the Graph Theoretic Analysis of the six systems is as follows.

6. Graph Theoretic Analysis of the systems

In a real life operating CCPP, thermal efficiency is deviated from design conditions due to the parameters epitomized in Fig. 6. Number for parameters for each system may vary from organization to organization due to design, location, maintenance etc. Therefore, a GTA based methodology developed for the analysis of CCPP system is further applied for the six systems to calculate REI for each system.

6.1. Performance Parameter Digraph (PPD) at system level

Digraphs for each system category are developed considering inheritance and interdependencies of design parameters. Nodes in the digraph represent the design parameters and their mutual interactions are depicted by different edges. Let inheritance of *N*th parameter of *i*th system is represented by E_N^i. Here subscript represents the parameter and superscript is for the system. PPD for each system category is developed and represented as below Figs. 7–12.

6.2. Matrix representation of PPD at system level

The Variable Permanent System Efficiency Parameter Matrix (VPSEPM) for six systems, for a general case with N design parameters, is represented as:

$$VPM = \begin{array}{c} \\ \\ \\ \\ \\ \\ \\ \end{array}\begin{array}{cccccc} E_1 & E_2 & E_3 & \ldots & \ldots & E_N \\ \left\{\begin{array}{c} E_1 \\ E_{21} \\ E_{31} \\ \ldots \\ \ldots \\ E_{N1} \end{array}\right. & \begin{array}{c} E_{12} \\ E_2 \\ E_{32} \\ \ldots \\ \ldots \\ E_{N2} \end{array} & \begin{array}{c} E_{13} \\ E_{23} \\ E_3 \\ \ldots \\ \ldots \\ E_{N3} \end{array} & \begin{array}{c} \ldots \\ \ldots \\ \ldots \\ \ldots \\ \ldots \\ \ldots \end{array} & \begin{array}{c} \ldots \\ \ldots \\ \ldots \\ \ldots \\ \ldots \\ \ldots \end{array} & \left.\begin{array}{c} E_{1N} \\ E_{2N} \\ E_{3N} \\ \ldots \\ \ldots \\ E_N \end{array}\right\} \end{array}\quad \begin{array}{c} Parameters(E_i) \\ E_1 \\ E_2 \\ E_3 \\ \ldots \\ \ldots \\ E_N \end{array} \tag{4}$$

It may be noted that above matrix represents inherent values of the design parameters that is E_i's ($i = 1, 2 \ldots, N$) and the interaction among design parameters is E_{ij}'s ($i, j = 1, 2 \ldots, N$ and $i \neq j$). VPSEPM (abbreviated as VPM_{System}) for each system PPD is developed. At the system level, corresponding to the digraph for air compressor system (Fig. 7) in general form is given by:

$$VPM_{AirCompressor} = \begin{array}{cc} \begin{array}{cccccc} E_1^1 & E_2^1 & E_3^1 & E_4^1 & E_5^1 & E_6^1 \end{array} & Parameter \\ \begin{bmatrix} E_1^1 & E_{12}^1 & E_{13}^1 & 0 & E_{15}^1 & E_{16}^1 \\ 0 & E_2^1 & 0 & 0 & 0 & E_{26}^1 \\ 0 & 0 & E_3^1 & E_{34}^1 & E_{35}^1 & 0 \\ 0 & 0 & E_{43}^1 & E_4^1 & 0 & 0 \\ 0 & 0 & 0 & 0 & E_5^1 & 0 \\ 0 & 0 & 0 & 0 & E_{65}^1 & E_6^1 \end{bmatrix} & \begin{array}{c} E_1^1 \\ E_2^1 \\ E_3^1 \\ E_4^1 \\ E_5^1 \\ E_6^1 \end{array} \end{array} \tag{5}$$

In the similar way, VPSEPM for other systems are written as:

PPD for Air Compressor System

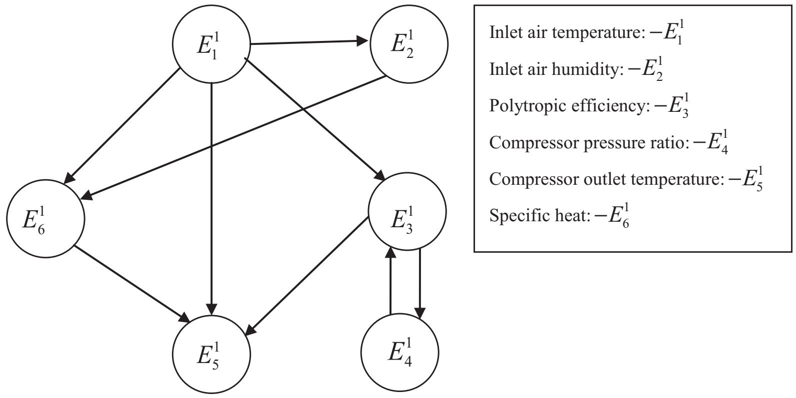

Figure 7 Digraph for air compressor system design parameters.

PPD for Combustion Chamber System

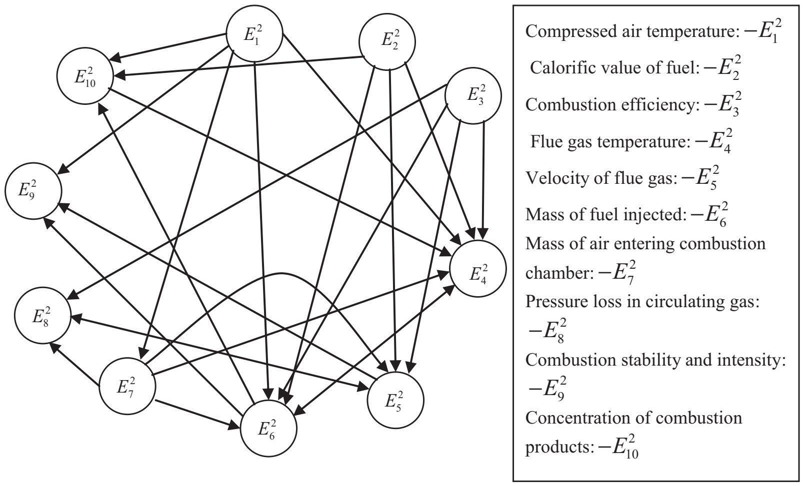

Figure 8 Digraph for combustion chamber system design parameters.

PPD for Gas Turbine System

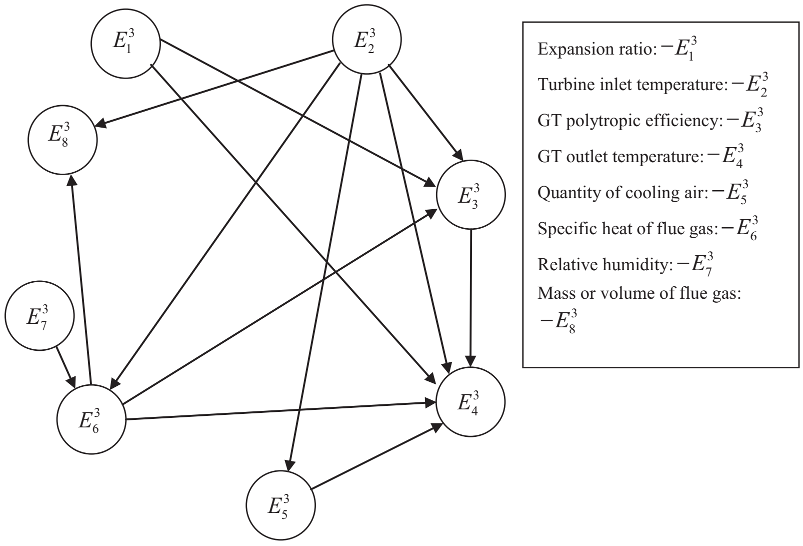

Figure 9 Digraph for gas turbine system design parameters.

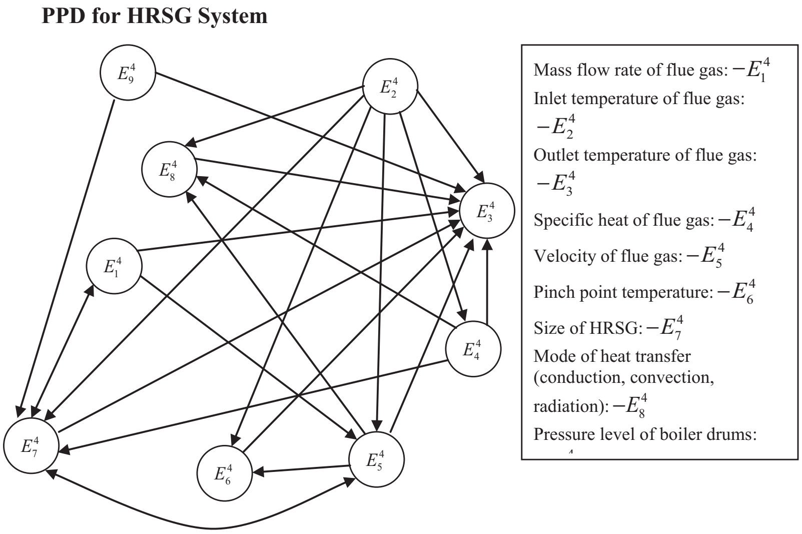

Figure 10 Digraph for HRSG system design parameters.

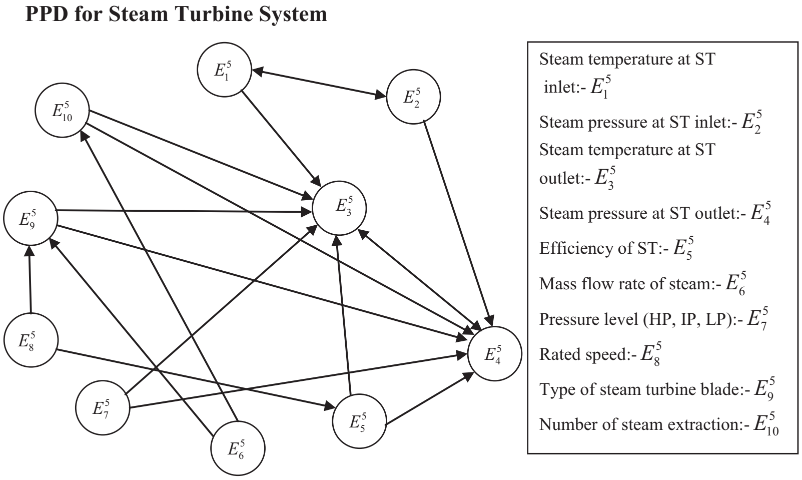

Figure 11 Digraph for steam turbine system design parameters.

$$VPM_{CombustionChamber} = \begin{array}{cccccccccc|c}
E_1^2 & E_2^2 & E_3^2 & E_4^2 & E_5^2 & E_6^2 & E_7^2 & E_8^2 & E_9^2 & E_{10}^2 & \mathit{Parameter} \\
E_1^2 & 0 & 0 & E_{14}^2 & 0 & E_{16}^2 & E_{17}^2 & 0 & E_{19}^2 & E_{110}^2 & E_1^2 \\
0 & E_2^2 & 0 & E_{24}^2 & E_{25}^2 & E_{26}^2 & 0 & 0 & 0 & E_{210}^2 & E_2^2 \\
0 & 0 & E_3^2 & E_{34}^2 & E_{35}^2 & E_{36}^2 & 0 & E_{38}^2 & 0 & 0 & E_3^2 \\
0 & 0 & 0 & E_4^2 & 0 & E_{46}^2 & 0 & 0 & 0 & 0 & E_4^2 \\
0 & 0 & 0 & 0 & E_5^2 & 0 & 0 & E_{58}^2 & E_{59}^2 & 0 & E_5^2 \\
0 & 0 & 0 & 0 & 0 & E_6^2 & 0 & 0 & E_{69}^2 & E_{610}^2 & E_6^2 \\
0 & 0 & 0 & E_{74}^2 & 0 & E_{76}^2 & E_7^2 & E_{78}^2 & 0 & 0 & E_7^2 \\
0 & 0 & 0 & 0 & E_{85}^2 & 0 & 0 & E_8^2 & 0 & 0 & E_8^2 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & E_9^2 & 0 & E_9^2 \\
0 & 0 & 0 & E_{104}^2 & 0 & 0 & 0 & 0 & 0 & E_{10}^2 & E_{10}^2
\end{array} \tag{6}$$

PPD for Water System

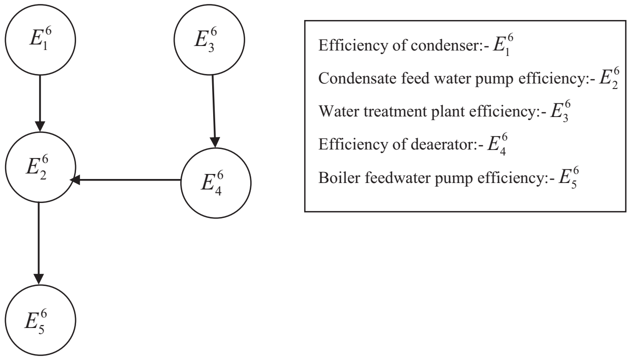

Figure 12 Digraph for water system design parameters.

$$VPM_{GasTurbine} = \begin{array}{cc} \begin{array}{cccccccc} E_1^3 & E_2^3 & E_3^3 & E_4^3 & E_5^3 & E_6^3 & E_7^3 & E_8^3 \end{array} & \mathit{Parameter} \\ \begin{bmatrix} E_1^3 & 0 & E_{13}^3 & E_{14}^3 & 0 & 0 & 0 & 0 \\ 0 & E_2^3 & E_{23}^3 & 0 & E_{25}^3 & E_{26}^3 & 0 & E_{28}^3 \\ 0 & 0 & E_3^3 & E_{34}^3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & E_4^3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & E_{54}^3 & E_5^3 & 0 & 0 & 0 \\ 0 & 0 & E_{63}^3 & 0 & 0 & E_6^3 & 0 & E_{68}^3 \\ 0 & 0 & 0 & 0 & 0 & E_{76}^3 & E_7^3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & E_8^3 \end{bmatrix} & \begin{array}{c} E_1^3 \\ E_2^3 \\ E_3^3 \\ E_4^3 \\ E_5^3 \\ E_6^3 \\ E_7^3 \\ E_8^3 \end{array} \end{array} \tag{7}$$

$$VPM_{HRSG} = \begin{array}{cc} \begin{array}{ccccccccc} E_1^4 & E_2^4 & E_3^4 & E_4^4 & E_5^4 & E_6^4 & E_7^4 & E_8^4 & E_9^4 \end{array} & \mathit{Parameter} \\ \begin{bmatrix} E_1^4 & 0 & E_{13}^4 & 0 & E_{15}^4 & 0 & E_{17}^4 & 0 & 0 \\ 0 & E_2^4 & E_{23}^4 & E_{24}^4 & E_{25}^4 & E_{26}^4 & E_{27}^4 & E_{28}^4 & 0 \\ 0 & 0 & E_3^4 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & E_{43}^4 & E_4^4 & 0 & 0 & E_{47}^4 & E_{48}^4 & 0 \\ 0 & 0 & E_{53}^4 & 0 & E_5^4 & E_{56}^4 & E_{57}^4 & E_{58}^4 & 0 \\ 0 & 0 & E_{63}^4 & 0 & 0 & E_6^4 & 0 & 0 & 0 \\ E_{71}^4 & 0 & E_{73}^4 & 0 & E_{75}^4 & 0 & E_7^4 & 0 & 0 \\ 0 & 0 & 0 & E_{84}^4 & 0 & 0 & 0 & E_8^4 & 0 \\ 0 & 0 & E_{93}^4 & 0 & 0 & 0 & E_{97}^4 & 0 & E_9^4 \end{bmatrix} & \begin{array}{c} E_1^4 \\ E_2^4 \\ E_3^4 \\ E_4^4 \\ E_5^4 \\ E_6^4 \\ E_7^4 \\ E_8^4 \\ E_9^4 \end{array} \end{array} \tag{8}$$

$$VPM_{WaterSystem} = \begin{array}{cc} \begin{array}{ccccc} E_1^6 & E_2^6 & E_3^6 & E_4^6 & E_5^6 \end{array} & \mathit{Parameter} \\ \begin{bmatrix} E_1^6 & E_{12}^6 & 0 & 0 & 0 \\ 0 & E_2^6 & 0 & 0 & E_{25}^6 \\ 0 & 0 & E_3^6 & E_{34}^6 & 0 \\ 0 & E_{42}^6 & 0 & E_4^6 & 0 \\ 0 & 0 & 0 & 0 & E_5^6 \end{bmatrix} & \begin{array}{c} E_1^6 \\ E_2^6 \\ E_3^6 \\ E_4^6 \\ E_5^6 \end{array} \end{array} \tag{10}$$

Matrix obtained from expressions 5–10 are of different order. Therefore, a generalized expansion of $N \times N$ matrix as permanent function is required so that matrix of any order can be analyzed.

6.3. Permanent function of PPD at system level

Permanent function of VPSEPM is called Variable Permanent System Efficiency Parameter Function, abbreviated as VPF-ep and for matrix (4) is written in sigma form in expression (11). Eq. (11) contains $N!$ terms organized in $N + 1$ groups, where N is number of elements. The physical implication of various grouping is elucidated as under:

- The first grouping epitomizes the measures of N design parameters.
- The second grouping is absent as there is no self-loop in the digraph.
- The third grouping encompasses 2-design parameters interaction loops and measures of $(N - 2)$ design parameters.
- Each term of the fourth grouping exemplifies a set of 3-design parameters interaction loop or its pair and measures of $(N - 3)$ design parameters.
- The fifth grouping comprises two subgrouping. The terms of the first subgrouping are a set of two 2-design parameters interaction loops and the measures of $(N - 4)$ design parameters. Each term of the second subgrouping is a set of 4-design parameters interaction loop or its pair and the measures of $(N - 4)$ design parameters.
- The sixth grouping encompasses two subgrouping. The terms of the first subgrouping is a set of 3-design parameters interaction loop or its pair and 2-design parameters interaction loop and the measures of $(N - 5)$ design parameters. Each term of the second subgrouping is a set of 5-design parameters interaction loop or its pair and the measures of $(N - 5)$ design parameters.

$$VPM_{SteamTurbine} = \begin{array}{cc} \begin{array}{cccccccccc} E_1^5 & E_2^5 & E_3^5 & E_4^5 & E_5^5 & E_6^5 & E_7^5 & E_8^5 & E_9^5 & E_{10}^5 \end{array} & \mathit{Parameter} \\ \begin{bmatrix} E_1^5 & E_{12}^5 & E_{13}^5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ E_{21}^5 & E_2^5 & 0 & E_{24}^5 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & E_3^5 & E_{34}^5 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & E_{43}^5 & E_4^5 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & E_{53}^5 & E_{54}^5 & E_5^5 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & E_6^5 & 0 & 0 & E_{69}^5 & E_{610}^5 \\ 0 & 0 & E_{73}^5 & E_{74}^5 & 0 & 0 & E_7^5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & E_{85}^5 & 0 & 0 & E_8^5 & E_{89}^5 & 0 \\ 0 & 0 & E_{93}^5 & E_{94}^5 & 0 & 0 & 0 & 0 & E_9^5 & 0 \\ 0 & 0 & E_{103}^5 & E_{104}^5 & 0 & 0 & 0 & 0 & 0 & E_{10}^5 \end{bmatrix} & \begin{array}{c} E_1^5 \\ E_2^5 \\ E_3^5 \\ E_4^5 \\ E_5^5 \\ E_6^5 \\ E_7^5 \\ E_8^5 \\ E_9^5 \\ E_{10}^5 \end{array} \end{array} \tag{9}$$

Correspondingly other terms of the expression are demarcated.

$$\begin{aligned} VPM = {} & \prod_1^N E_i + \sum_i\sum_j\sum_k\sum_l\cdots\sum_N E_{ij}E_{ji}E_kE_l\cdots E_N \\ & + \left\{\sum_i\sum_j\sum_k\sum_l\cdots\sum_N (E_{ij}E_{jk}E_{ki})E_lE_m\cdots E_N\right. \\ & \left. + \sum_i\sum_j\sum_k\sum_l\cdots\sum_N (E_{ik}E_{kj}E_{ji})E_lE_m\cdots E_N + \right\} \\ & + \left[\left\{\sum_i\sum_j\sum_k\sum_l\cdots\sum_N (E_{ij}E_{ji})(E_{kl}E_{lk})E_mE_n\cdots E_N\right\}\right. \\ & + \left\{\sum_i\sum_j\sum_k\sum_l\cdots\sum_N (b_{ij}b_{jk}b_{kl}b_{li})B_mB_n\cdots B_N\right. \\ & \left.\left. + \sum_i\sum_j\sum_k\sum_l\cdots\sum_N (E_{il}E_{lk}E_{kj}E_{ji})E_mE_n\cdots E_N\right\}\right] \\ & + \left[\left\{\sum_i\sum_j\sum_k\sum_l\cdots\sum_N (E_{ij}E_{ji})(E_{kl}E_{lm}E_{mk})E_nE_o\cdots E_N\right.\right. \\ & \left. + \sum_i\sum_j\sum_k\sum_l\cdots\sum_N (E_{ij}E_{ji})(E_{km}E_{ml}E_{lk})E_nE_o\cdots E_N\right\} \\ & + \left\{\sum_i\sum_j\sum_k\sum_l\cdots\sum_N (E_{ij}E_{jk}E_{kl}E_{lm}E_{mi})E_nE_o\cdots E_N\right. \\ & \left.\left. + \sum_i\sum_j\sum_k\sum_l\cdots\sum_N (E_{im}E_{ml}E_{lk}E_{kj}E_{ji})E_nE_o\cdots E_N\right\}\right] + \cdots \end{aligned} \tag{11}$$

Quantification of inheritance and interdependencies of design parameters may be established with the help of industrial data or literature survey. If industrial data are not available then quantification of diagonal elements of matrix can be done on a scale of 1–9 as given in Table 1, based on the inheritance of each design parameters. Interdependency is decided on the scale of 1–5 as per Table 2. The values of permanent functions of six systems are used for the calculation of REI for CCPP as explained in the next section.

7. REI for systems

Combined cycle power plant efficiency analysis is highly complex because of interaction among systems and design parameters. For simplification every system is studied individually by considering inheritance and interdependencies of design parameters. In present analysis REI for each system is calculated and subsequently used for CCPP efficiency analysis. REI for each system is the ratio of real time efficiency $(Efficiency)_{RealTime}$ to designed efficiency $(Efficiency)_{Design}$. If system is operating at its best then REI is one otherwise it will be lesser than one because no system can perform better than its design performance (efficiency in present case).

If any system is affected by more number of parameters then its VPSEPM is of higher order. After quantification its permanent function is of higher value in comparison with a system being affected by lesser number of parameters. In this case value of permanent is affected by number of parameters and true picture of system efficiency cannot be had from the index. By using the concept of REI, this problem is resolved. The value of REI is between 0 and 1 for each system and it is easy to handle and interpret. For complete analysis of any system it is necessary to develop VPSEPM at system level by taking the inheritance and interdependency of each design parameter in real time and designed conditions. If the VPF-ep for real time and design is represented by $(Efficiency)_{RealTime}$ and $(Efficiency)_{Design}$ respectively then the value of REI for six systems is given by following relations:

$$REI_{AirCompressor} = \frac{(Efficiency)_{RealTimeAirCompressor}}{(Efficiency)_{DesignAirCompressor}} \tag{12}$$

$$REI_{CombustionChamber} = \frac{(Efficiency)_{RealTimeCombustionChamber}}{(Efficiency)_{DesignCombustionChamber}} \tag{13}$$

$$REI_{GasTurbine} = \frac{(Efficiency)_{RealTimeGasTurbine}}{(Efficiency)_{DesignGasTurbine}} \tag{14}$$

$$REI_{HRSG} = \frac{(Efficiency)_{RealTimeHRSG}}{(Efficiency)_{DesignHRSG}} \tag{15}$$

$$REI_{SteamTurbine} = \frac{(Efficiency)_{RealTimeSteamTurbine}}{(Efficiency)_{DesignSteamTurbine}} \tag{16}$$

$$REI_{WaterSystem} = \frac{(Efficiency)_{RealTimeWaterSystem}}{(Efficiency)_{DesignWaterSystem}} \tag{17}$$

The values obtained for REI of the six systems from the equations mentioned above provide guidance for the quantification of diagonal element (inheritance) in Eq. (1). The value of the permanent function obtained in this way is dependent on inheritance and interdependencies of design parameters and systems.

8. Step by step for procedure determining REI_{CCPP}

A methodology for the evaluation of REI_{CCPP} is proposed based on GTA as discussed above. The main steps of this methodology are as follows:

1. Identify the various systems affecting the CCPP efficiency in such a way that no system is independent.
2. Develop SED showing all possible interconnections in between systems. This is the digraph at the system level.
3. Identify the various design parameters affecting system's efficiency for each system.
4. For each system, develop a digraph among the design parameters based on the interactions among them. This is the digraph at each system level.
5. Based on the above-mentioned digraphs at system level for design parameters, develop the variable permanent system efficiency parameter matrix for each system.
6. Calculate the variable permanent system efficiency parameter function at each system level. For avoiding the complexity, the numerical values of inheritance and interactions may be used.
7. The value of REI at system level is calculated with the help of expressions (12)–(17) for all six systems.
8. Develop the VPSEPM for the SED developed in step 2. This will be $M \times M$ matrix with diagonal elements of D_i and off-diagonal elements of d_{ij}. The value of REI calculated at system level in step 7 provides guidance for inheritance (diagonal elements of D_i) for each system category. The values of interaction among these systems

(i.e. off-diagonal elements of d_{ij}) can be decided by industrial data or literature survey.

9. Calculate the variable permanent system efficiency function for CCPP system. This is the value of CCPP efficiency index based on the different design parameters and their interdependency.
10. Compare different power plants in terms of CCPP efficiency index and list them in descending order of their index values. The power plant having the lowest index value of has the best chance of efficiency improvement.

9. Efficiency analysis

In this section the value of CCPP efficiency is calculated. For this purpose, some numerical values of all parameters and their interdependencies are required i.e. the value of all terms of VPM$_{CCPP}$(expression 1). The value of diagonal elements in VPM$_{CCPP}$, i.e., the value of all six systems D_1, D_2, D_3, D_4, D_5 and D_6 are evaluated by applying GTA for design parameters of the respective system. The methodology explained in the Sections 2–7 is used to evaluate CCPP efficiency index.

1. Various system categories affecting the CCPP efficiency are identified and presented in Fig. 2.
2. A digraph is developed for these six systems as shown in Fig. 4.
3. Design parameters are identified for each category of CCPP system and presented in Fig. 6.
4. Digraphs for each system have been developed in Section 4 and they are represented by Figs. 7–12.
5. At system level, Tables 1 and 2 are used to determine numerical values for inheritance of parameters and their interactions. The VPSEPM for six systems are corresponding to Eqs. (5)–(10) and after quantification they are as written below:

$$E^1 = VPM_{AirCompressor} = \begin{array}{cc} \begin{matrix} E_1^1 & E_2^1 & E_3^1 & E_4^1 & E_5^1 & E_6^1 \end{matrix} & \textit{Design Parameters} \\ \begin{bmatrix} 9 & 3 & 4 & 0 & 3 & 5 \\ 0 & 1 & 0 & 0 & 0 & 2 \\ 0 & 0 & 9 & 5 & 4 & 0 \\ 0 & 0 & 3 & 5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 3 \end{bmatrix} & \begin{matrix} E_1^1 \\ E_2^1 \\ E_3^1 \\ E_4^1 \\ E_5^1 \\ E_6^1 \end{matrix} \end{array} \tag{18}$$

$$E^2 = VPM_{CombustionChamber} = \begin{array}{cc} \begin{matrix} E_1^2 & E_2^2 & E_3^2 & E_4^2 & E_5^2 & E_6^2 & E_7^2 & E_8^2 & E_9^2 & E_{10}^2 \end{matrix} & \textit{Design Parameters} \\ \begin{bmatrix} 9 & 0 & 0 & 5 & 0 & 4 & 4 & 0 & 2 & 1 \\ 0 & 9 & 0 & 5 & 1 & 5 & 0 & 0 & 0 & 3 \\ 0 & 0 & 8 & 3 & 1 & 2 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 5 & 0 & 0 & 4 & 4 & 0 \\ 0 & 0 & 0 & 0 & 0 & 4 & 0 & 0 & 3 & 1 \\ 0 & 0 & 0 & 1 & 0 & 4 & 7 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 3 & 0 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 5 & 0 \\ 0 & 0 & 0 & 3 & 0 & 0 & 0 & 0 & 0 & 6 \end{bmatrix} & \begin{matrix} E_1^2 \\ E_2^2 \\ E_3^2 \\ E_4^2 \\ E_5^2 \\ E_6^2 \\ E_7^2 \\ E_8^2 \\ E_9^2 \\ E_{10}^2 \end{matrix} \end{array} \tag{19}$$

$$E^3 = VPM_{GasTurbine} = \begin{array}{cc} \begin{matrix} E_1^3 & E_2^3 & E_3^3 & E_4^3 & E_5^3 & E_6^3 & E_7^3 & E_8^3 \end{matrix} & \textit{Design Parameters} \\ \begin{bmatrix} 9 & 0 & 4 & 5 & 0 & 0 & 0 & 0 \\ 0 & 8 & 1 & 0 & 4 & 5 & 0 & 3 \\ 0 & 0 & 9 & 4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 4 & 6 & 0 & 0 & 0 \\ 0 & 0 & 3 & 0 & 0 & 6 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 \end{bmatrix} & \begin{matrix} E_1^3 \\ E_2^3 \\ E_3^3 \\ E_4^3 \\ E_5^3 \\ E_6^3 \\ E_7^3 \\ E_8^3 \end{matrix} \end{array} \tag{20}$$

$$E^4 = VPM_{HRSG} = \begin{array}{cc} \begin{matrix} E_1^4 & E_2^4 & E_3^4 & E_4^4 & E_5^4 & E_6^4 & E_7^4 & E_8^4 & E_9^4 \end{matrix} & \textit{Design Parameters} \\ \begin{bmatrix} 9 & 0 & 2 & 0 & 4 & 0 & 1 & 0 & 0 \\ 0 & 9 & 4 & 5 & 3 & 2 & 1 & 5 & 0 \\ 0 & 0 & 5 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 3 & 6 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 4 & 0 & 8 & 2 & 5 & 1 & 0 \\ 0 & 0 & 4 & 0 & 0 & 6 & 0 & 0 & 0 \\ 5 & 0 & 4 & 0 & 3 & 0 & 7 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 5 & 0 \\ 0 & 0 & 4 & 0 & 0 & 0 & 5 & 0 & 7 \end{bmatrix} & \begin{matrix} E_1^4 \\ E_2^4 \\ E_3^4 \\ E_4^4 \\ E_5^4 \\ E_6^4 \\ E_7^4 \\ E_8^4 \\ E_9^4 \end{matrix} \end{array} \tag{21}$$

$$E^5 = VPM_{SteamTurbine} = \begin{array}{cccccccccc|c} E_1^5 & E_2^5 & E_3^5 & E_4^5 & E_5^5 & E_6^5 & E_7^5 & E_8^5 & E_9^5 & E_{10}^5 & \textit{Design Parameters} \\ \hline 9 & 2 & 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & E_1^5 \\ 2 & 9 & 0 & 3 & 0 & 0 & 0 & 0 & 0 & 0 & E_2^5 \\ 0 & 0 & 9 & 2 & 0 & 0 & 0 & 0 & 0 & 0 & E_3^5 \\ 0 & 0 & 2 & 9 & 0 & 0 & 0 & 0 & 0 & 0 & E_4^5 \\ 0 & 0 & 4 & 4 & 8 & 0 & 0 & 0 & 0 & 0 & E_5^5 \\ 0 & 0 & 0 & 0 & 0 & 7 & 0 & 0 & 4 & 3 & E_6^5 \\ 0 & 0 & 4 & 4 & 0 & 0 & 9 & 0 & 0 & 0 & E_7^5 \\ 0 & 0 & 0 & 0 & 3 & 0 & 0 & 5 & 5 & 0 & E_8^5 \\ 0 & 0 & 3 & 3 & 0 & 0 & 0 & 0 & 5 & 0 & E_9^5 \\ 0 & 0 & 3 & 3 & 0 & 0 & 0 & 0 & 0 & 4 & E_{10}^5 \end{array} \tag{22}$$

$$E^6 = VPM_{WaterSystem} = \begin{array}{ccccc|c} E_1^6 & E_2^6 & E_3^6 & E_4^6 & E_5^6 & \textit{Design Parameters} \\ \hline 9 & 5 & 0 & 0 & 0 & E_1^6 \\ 0 & 7 & 0 & 0 & 5 & E_2^6 \\ 0 & 0 & 7 & 5 & 0 & E_3^6 \\ 0 & 3 & 0 & 9 & 0 & E_4^6 \\ 0 & 0 & 0 & 0 & 7 & E_5^6 \end{array} \tag{23}$$

6. The value of permanent function for each category is calculated using a computer program developed in language C^{++}. The values of permanent function of different systems are written as under:
   Per $[E^1]$ = 1620
   Per $[E^2]$ = 2.3882×10^7
   Per $[E^3]$ = 186624
   Per $[E^4]$ = 4.5730×10^7
   Per $[E^5]$ = 3.6414×10^8
   Per $[E^6]$ = 27783
7. Now for example Turbine Inlet Temperature (TIT) is decreased from 1300 °C to 1100 °C and inheritance of the gas turbine system is 7 in place 8, then expression (20) will become as represented in expression (24). Estimation for the change in inheritance from 8 to 7 with decrease in TIT from 1300 °C (1573 K) to 1100 °C (1373 K) can be had from the physical entity such as $(1573/1373) \cong (8/7)$.

$$VPM_{GasTurbineRealTime} = \begin{array}{cccccccc|c} E_1^3 & E_2^3 & E_3^3 & E_4^3 & E_5^3 & E_6^3 & E_7^3 & E_8^3 & \textit{Design Parameters} \\ \hline 9 & 0 & 4 & 5 & 0 & 0 & 0 & 0 & E_1^3 \\ 0 & 7 & 1 & 0 & 4 & 5 & 0 & 3 & E_2^3 \\ 0 & 0 & 9 & 4 & 0 & 0 & 0 & 0 & E_3^3 \\ 0 & 0 & 0 & 4 & 0 & 0 & 0 & 0 & E_4^3 \\ 0 & 0 & 0 & 4 & 6 & 0 & 0 & 0 & E_5^3 \\ 0 & 0 & 3 & 0 & 0 & 6 & 0 & 1 & E_6^3 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & E_7^3 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & E_8^3 \end{array} \tag{24}$$

$VPM_{GasTurbineDesign}$ will be as expression (20). The value of REI for gas turbine is calculated as expression (14). It is the ratio of permanent function of matrix of expression (24)–(20). Let the permanent functions of (24) and (20) are represented by (VPF-e gas turbine)$_{RealTime}$ and (VPF-e gas turbine)$_{Design}$ then REI for gas turbine is represented by the expression as follows:

$$REI_{GASTURBINE} = \frac{(VPF - e \text{ gas turbine})_{RealTime}}{(VPF - e \text{ gas turbine})_{Design}} = \frac{163296}{186624} = .875 \tag{25}$$

8. In the plant when all the systems are working at their design value then REI for each system will be 1. If it is not working at designed conditions then value for REI is between 0 and 1. If all the systems of CCPP are working at their maximum efficiency, which is the ideal case, then VPSEM for CCPP system corresponding to the expression (1) is:

$$VPM_{CCPPIsentropic} = \begin{array}{cccccc|c} 1 & 2 & 3 & 4 & 5 & 6 & \textit{Systems} \\ \hline 9 & 5 & 3 & 0 & 0 & 0 & 1 \\ 0 & 9 & 5 & 0 & 0 & 0 & 2 \\ 3 & 0 & 9 & 4 & 0 & 0 & 3 \\ 0 & 2 & 5 & 9 & 5 & 2 & 4 \\ 0 & 0 & 0 & 3 & 9 & 3 & 5 \\ 0 & 0 & 0 & 3 & 3 & 9 & 6 \end{array} \tag{26}$$

But for a practical system, it is not possible to give 100% efficiency. In actual life power plant is performing its best when it is operating at design conditions. Corresponding to these design specifications, the quantified values of inheritance for air compressor system, combustion chamber system, gas turbine system, HRSG system, steam turbine system and water system is obtained iteratively and these are 8.5, 7, 8.5, 8, 8.5 and 7 respectively. Corresponding to the design efficiency of different systems of CCPP, VPSEM is as given below:

$$VPM_{CCPPDesign} = \begin{array}{cccccc|c} 1 & 2 & 3 & 4 & 5 & 6 & \textit{Systems} \\ \hline 8.5 & 5 & 3 & 0 & 0 & 0 & 1 \\ 0 & 7 & 5 & 0 & 0 & 0 & 2 \\ 3 & 0 & 8.5 & 4 & 0 & 0 & 3 \\ 0 & 2 & 5 & 8 & 5 & 2 & 4 \\ 0 & 0 & 0 & 3 & 8.5 & 3 & 5 \\ 0 & 0 & 0 & 3 & 3 & 7 & 6 \end{array} \tag{27}$$

Table 3 Comparison of results for CCPP efficiency.

Type of cycle	V94.3 η_{ccpp} (%) (Bolland, [2])	V94.3 η_{ccpp} (%) (GTA)
Dual pressure	53.61	53.54
Dual pressure reheat	54.06	53.92
Dual pressure with supercritical reheat	54.60	54.72
Triple pressure	54.12	54.32
Triple pressure reheat	54.57	54.72
Triple pressure with supercritical reheat	55.03	55.12

The quantification of diagonal and non-diagonal elements in the matrices (26) and (27) is done corresponding to the data available in the literature (Bolland, [2]). For the validation of methodology, data available in literature (Bolland, [2]) for other configuration are also used. Efficiency for a CCPP is the ratio of permanent of Eq. (27) to the permanent of Eq. (26).

$$Efficiency_{CCPP} = \frac{Per(VPM_{CCPPDesign})}{Per(VPM_{CCPPIsentropic})} \times 100 = \frac{598561}{1118070} \times 100 = 53.54\% \tag{28}$$

In the similar manner results obtained for the other configurations are shown in the Table 3 and they are found in good agreement with the results available in literature. The values of inheritance for different systems are considered based on design data available in literature (Bolland, [2]).As calculated in step 7, for the decrease in TIT from 1300 °C to 1100 °C REI for gas turbine system is 0.875 of the designed value. Therefore, $VPM_{CCPPRealTime}$ corresponding to expression (27) is written as follows:

$$VPM_{CCPPRealTime} = \begin{array}{c} \\ \\ \\ \\ \\ \\ \\ \end{array}\begin{array}{cc} \begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & 6 \end{array} & Systems \\ \begin{bmatrix} 8.5 & 5 & 3 & 0 & 0 & 0 \\ 0 & 7 & 5 & 0 & 0 & 0 \\ 3 & 0 & (.875\times 8.5) & 4 & 0 & 0 \\ 0 & 2 & 5 & 8 & 5 & 2 \\ 0 & 0 & 0 & 3 & 8.5 & 3 \\ 0 & 0 & 0 & 3 & 3 & 7 \end{bmatrix} & \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{array} \end{array} \tag{29}$$

9. Value of permanent function for the design case (expression 27) is 1,118,070 and for the real time case (expression 29) is 54,8361. Value of relative efficiency for CCPP comes out to be 49.04%. From the GTA it came out that with decrease in TIT from 1300 °C to 1100 °C, efficiency is decreased from 53.54% to 49.04%. Results obtained from GTA are in agreement with the results available in literature.
10. CCPP efficiency calculated with the help of GTA, depends upon the inheritance and interdependencies of systems and design parameters. By carrying out similar analysis, the efficiency index for different CCPP system can be obtained.

10. Exergoeconomic analysis

Exergy analysis is unanimously acknowledged as thermo-numeric method of efficiency analysis for real life operating industrial processes which allow the localization and accounting the degree of inefficiency of components in a system [48]. Exergoeconomic analysis technique is coalescence of first and second laws of thermodynamics with monetary cost balances conducted at the system and component level. It is helpful to understand the cost formation process, minimize the overall product costs and assign costs to the different products produced in the processes. It provides a rationale for assessing the cost of products in terms of natural resources and their impact on the environment, and helps to optimize and synthesize very complex energy systems [49]. It is mainly used for the cost accounting, diagnosis, improvement, design and optimization of thermal systems. In the literature it is reported that no other technique ever devised can go from physics to economics at the system component level [49]. Business managers use cost data for decision-making and performance evaluation and control. Conventional simulators provide information about alteration in resources consumption with change in specified circumstances but they do not provide an integrated answer of the economic and the energy effects of any malfunction [50].

It is also reported in the literature [51,52] that economics and efficiency of power plant is the function of design parameters of its components. Complexity of system analysis is enhanced due to interdependency in-between economics and efficiency. Costs functional for the components are also interdependent. For example compressor pressure ratio is to be equal to the gas turbine expansion ratio. Furthermore, literature [18,29] reports that to increase cycle efficiency, it is required to select the gas turbine with higher turbine inlet temperature along with higher cycle pressure ratio. Therefore, all the other design parameters for the power plant components are to be rescheduled with change in one design parameters.

In the economic analysis of the thermal systems such as power plant, the annual values of carrying charges, fuel costs, raw water costs, and operating and maintenance (O&M) expenses supplied to the overall system are the necessary input data. However, these cost components may vary significantly within the economic life. The cost data for carrying charges, fuel, raw water, O&M are obtained from the company. Therefore, a flexible model capable of incorporating any number of interdependent tangible and intangible parameters or sub-parameters is helpful in exergoeconomic analysis.

For the demonstration of the proposed methodology in the field of exergoeconomic analysis an example is deliberated. In the expression (27), that is design efficiency VPSEM, represents the level of exergy destruction also. Diagonal elements of the matrix are to represent the inheritance of six systems and alternatively represent the efficiency of systems. If the system efficiency is improved then exergy utilization is better and corresponding value of index is also improved.

In a real life situation the cost of the system is increased with increase in its efficiency. It is mentioned in the literature that Graph theoretic models have adaptability to model any of the reliability, availability, maintainability and cost characteristics by associating suitable attributes to the nodes and edges of the SSG [53]. Therefore, SSG in Fig. 2 can be modeled in system cost graph. The nodes in the graph represent the cost of the system and edges represent the interdependency of one system cost on the other. Let the nodes are represented by G_i and edges are represented with g_{ij} then system cost digraph (SCD) corresponding to the Fig. 3 is as shown in Fig. 13.

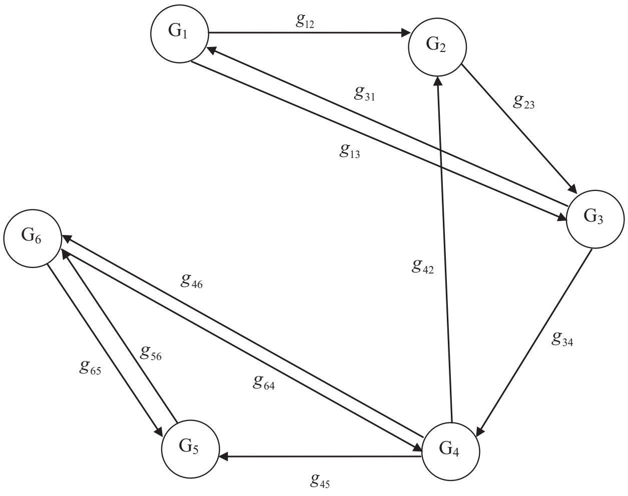

Figure 13 Digraph showing the cost of six systems and their interdependencies.

The matrix development for the digraph shown in Fig. 13 is similar as explained in Section 4.2 of this work. The matrix representation corresponding to the system cost digraph of Fig. 13 is called as Variable Permanent System Cost Matrix (VPSCM) G_c and is as represented in expression (30).

$$G_c = \begin{bmatrix} G_1 & g_{12} & g_{13} & 0 & 0 & 0 \\ 0 & G_2 & g_{23} & 0 & 0 & 0 \\ g_{31} & 0 & G_3 & g_{34} & 0 & 0 \\ 0 & g_{42} & g_{43} & G_4 & g_{45} & g_{46} \\ 0 & 0 & 0 & g_{54} & G_5 & g_{56} \\ 0 & 0 & 0 & g_{64} & g_{65} & G_6 \end{bmatrix} \tag{30}$$

The permanent function of VPSCM is called the variable permanent system cost function and is abbreviated as VPF-c. For its evaluation diagonal and non-diagonal elements are to be quantified suitably. It is experienced that different power plant components have different economic value with varying exergy utilization. There are varying degrees of influences among the different components. It is suggested that these relationships among components, need to be determined by a team from different functional groups, who are involved in purchase, maintenance and operation activities, whether directly or indirectly. If it is not possible to measure any parameter directly then, qualitative values may be adopted. Therefore, diagonal elements in the VPSCM are to be assigned value corresponding to the increase and decrease of cost with their respective exergy utilization.

If a quantitative value for inheritance is not available, then a ranked value judgement on a scale (*e.g.*, from 1 to 9) is adopted. Table 1 is suggested for this purpose. To assign numerical values to the interdependence of parameters the opinions of experts can be recorded. These qualitative values of the interdependence of enablers are also assigned on a scale (*e.g.*, 1–5), as suggested in Table 2.

For the exergoeconomic analysis VPF-c and VPF-e are to be coupled with the help of graph theory so that result is in the form of single numerical index. As the VPF-c and VPF-e are calculated with the same methodology and results are in the form of dimensionless number, therefore, it is easy to carry out exergoeconomic analysis with the methodology developed in the present work. As the exergy utilization and purchase cost are interdependent, then the system exergoeconomic digraph is as represented in Fig. 14.

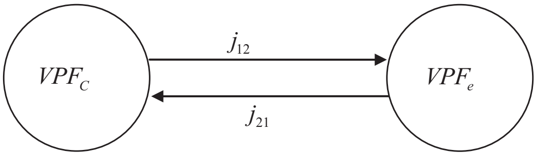

Figure 14 Digraph showing the exergoeconomic interdependencies.

The exergoeconomic permanent matrix corresponding to the performance parameter graph shown in Fig. 14 is as represented by the following expression

$$J = \begin{bmatrix} VPF_C & j_{12} \\ j_{21} & VPF_e \end{bmatrix} \tag{31}$$

The permanent function corresponding to the above expression called as exergoeconomic permanent function and represented as follows

$$J_P = VPF_C VPF_e + j_{12} j_{21} \tag{32}$$

The composite index developed above takes care of exergy, economy and their interdependency. An upper and lower limit of index may be fixed for decision making corresponding to the resources available with the organization. With the help of the proposed methodology plant owner may maintain an opinion for future improvements by decreasing the unit exergy cost of the investigated plants and checking the exergy consumption locations within the plants.

11. Results

In the present work, a methodology based upon GTA is proposed and with the help of two examples, its applications for the efficiency and exergoeconomic analysis are demonstrated. For the analysis, a large system such as CCPP is divided into sub-systems. The interactions among its sub-systems are identified. Performance of these sub-systems is influenced by a large number of parameters which are interdependent. In the present work methodology based upon GTA is developed for system level analysis and then extended to sub-system level. Digraphs developed at system and sub-system level are converted into matrix form. The matrix is developed in the form of permanent function and after quantification of inheritance and interdependencies it is evaluated with the help of computer programming tool. Results obtained from the proposed methodology are in line with the results available in literature.

In the present analysis CCPP is divided into six subsystems. If at some stage, management personals found it suitable then number of subdivisions may be increased and analysis may be carried out with same GTA methodology. In the present work REI is calculated for efficiency analysis at system and subsystem level. If the number of subsystems or parameters is changed, even then index will remain in-between 0–1. If the concept of REI is not used then index value is dependent on the number of subsystem and parameters. Therefore, it is convenient to handle the score obtained by the methodology developed in the present work.

12. Conclusion

Decision making is indefinite process, outcomes of which are dependent on the number of situations analyzed and category of expertise available. A tool is required to analyze and compare different kinds of options available so that best one may be opted. The tool should be easy to handle, flexible enough to incorporate the changes with lesser computational efforts. Accuracy of tool in case of decision making is dependent on the figures and expertise available with the management. In case of CCPP there are many performance parameters (e.g. efficiency, reliability, maintainability, availability, etc.) which have to be a part of MADM and each one is analyzed with different approaches. Out of these parameters, efficiency is one of the most important parameter of decision making. From design to life time operation of power plant its incessant assessment is required. Further it is needed that assessment of efficiency should be in such a manner that it may be incorporated with other parameters (e.g. reliability, maintainability, etc.) easily. In the present work GTA is selected with a view that it is qualitative cum quantitative method. The GTA developed for efficiency analysis can be used for reliability, maintainability, availability and cost analysis also. A common guiding principle provided by GTA is helpful to develop an index integrating all the parameters to be analyzed for CCPP performance estimation.

The increasing or decreasing order of efficiency is just for ranking of power plants but managers should mainly focus on the performance parameters according to which some major decision regarding power plant performance on efficiency basis can be taken. REI may be used for the following analysis.

1. Index may be used to evaluate the efficiency of combined cycle power plant in real time situation and it may be used to compare with the design index value. From this weak parameters may be identified and improved so that plant may achieve design value.
2. Efficiency index may be used in combination with other operating parameters such as reliability and performance of power plant may be represented by single numerical index which is easy to analyze.
3. Efficiency of two or more real life operating power plants may be compared with the help of index and they may be arranged in the descending order of their efficiency.
4. If any suggestion is given by some manufacturer for the improvement in the plant then some quantitative results may be calculated to check weather the improvement is beneficial or not.

In the era of competition, early decision with the help of some mathematical method with logical reasoning is helpful to make the presence in global market. A complex and large system such as CCPP require analyzing large number of operating parameters to achieve the goal of organization. For this purpose the methodology developed in this section may be helpful to take the organization one step forward.

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