PERFORMANCE EVALUATION AND ECONOMIC ANALYSIS OF A STEAM THERMAL POWER PLANT

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ABSTRACT

Performance evaluation and economic analysis is carried out to predict the steady state operational availability and net present value index for a thermal power plant. Mathematical formulation of the plant's reliability is carried out using probability theory following the Chapman-Kolmogorov Birth-Death process. The system of differential equations obtained is solved using the Laplace transformation technique. The behaviour analysis of performance modules reveals that availability decreases with increasing failure rates, while operational availability improves with an initial increase in repair rates for different sub-systems. From the economic evaluation module, the plant availability and power generation capacity are found to be sensitive, while increasing the redundancies of feed pump or condensate extraction pump sub-systems has less influence on the profitability index. A high-capacity plant reflects better trends. Model predictions indicate a critical condition for repair rates; beyond these rates the plant availability, net present value, and annual revenue earned are found to be insensitive.

OPSOMMING

Prestasiebepaling en teenswoordige ontleding word uitgevoer om gestadigde operasionele beskikbaarheid en 'n netto teenswoordige indekswaarde vir 'n fossielbrandstofkragstasie te bepaal. 'n Wiskundige model vir aanlegbetroubaarheid word probabilisties geskep met gebruik van die Chapman-Kolmogorov metode. Die model se differensiaalvergelykings word gemanipuleer met gebruik van Laplace-transformasie. Die resulterende sisteemprestasie toon dat beskikbaarheid afneem met toenemende mislukkingstempo's en *vice versa*. Die ekonomiese ontleding van die model toon sensitiwiteit by lewering van drywing en beskikbaarheid, en dat oortolligheid van sekere hulpsubsisteme nie betekenisvol tot winsgewendheid bydra nie. Die model benadeel die belangrikheid van hersteltempo's.

1. INTRODUCTION

Over the years, as engineering systems have become more complex and sophisticated, the performance evaluation of engineering systems has become increasingly important because of factors such as cost, risk of hazard, competition, public demand, and use of new technology. A high reliability level is desirable to reduce overall costs of production and risk of hazards in larger, more complex and sophisticated systems such as thermal power plants. It is necessary that the steam thermal power plant provide a reliable and uninterrupted electrical supply for long periods.

Considerable efforts have been made by researchers providing general methods for performance evaluation, designing equipment with specified reliability figures, demonstration of reliability values [4], issues of maintenance, inspection, repair and replacement, and the notion of maintainability as a design parameter [3]. From a purely economic point of view, in areas involving very high risk, or in those that require high safety measures (e.g. space vehicles), high reliability figures should be sought; while in areas where the cost of production or service is important, optimum performance figures – subject to a constraint on the cost – are to be welcomed [5]. Studies on the economic analysis of thermal power plants are also reported in the literature [4-7].

Tewari *et al* (2007) discuss the performance modeling and decision support system of a feed water system of a thermal power plant. Tewari *et al.* (2008) discuss the performance modeling and behavioral analysis of a coal handling system of a thermal power plant. [10-11]

To obtain the regular and economical generation of electrical power, plants should be maintained at a sufficiently high availability level corresponding to minimum overall cost. This paper presents a 'performance evaluation model' for steam thermal power plant to predict the operational availability and profitability index. Sensitivity analysis is also presented to examine the effect of repair rates on operational availability, various costs, and profitability index.

NOMENCLATURE

□	System breakdown
○	System operation successful
Av	Availability of thermal power plant
C	Condenser sub-system (I=3)
C_i	Constants used in eq. (13) defined in Appendix A
CI_T	Initial capital investment (€)
CI_I	Initial capital investment in equipment (€)
CO_y	Operating cost (€/yr)
CR_y	Annual revenue earned (€/yr)
CO_L	Labour costs (€/yr)
CO_F	Fuel purchased cost (€/yr)
CO_{repair}	Maintenance cost (€/yr)
CO_{insgen}	Insurance and general cost (€/yr)
C_{PL}	Personnel average salary (€/yr)
C_{EP}	Current market price of electricity (€/M_W)
dr	Discount rate
f_{auxil}	a factor (account for energy consumed to operate the auxiliaries
G	Generator sub-system (I=6)
hr_{up}	Annual operating hours of the plant
lhv_F	Heating value of fuel
m_F	Annual fuel (coal) consumption
M_W	Plant capacity (MW)
n_{ph}	Total sub-systems of condensate extraction pumps employed
n_{pb}	Total sub-systems of feed pumps employed
n_L	Total manpower employed in the plant on annual basis

ny	Plant life (years)
$P_l(t)$	Time derivative for probability of a event at time t
$P_0(t)$	Probability that at time t all sub-systems are in original working state (without standby mode)
$P_l(t)$	Probability that at time t all sub-systems are in full load condition (standby mode) for l =4,5,12.
$P_l(t)$	Probability. that at time t all sub-systems are in the breakdown state for l= 1-3, 6-11, 13-23.
P_F	Economic profitability index (€)
P_h	Condensate extraction pump (l=4)
P_b	Feed pump (l=5)
S	Steam boiler sub-system (l=1)
T	Turbine sub-system (l=2)
Δt	Time increment
η_{ov}	Overall thermal efficiency of the plant
λ_l	Failure rate of l^{th} sub-system (failures/hr)
α_l	Repair rate of l^{th} sub-system (repairs/hr)

2. MODEL DESCRIPTION AND FORMULATION

A steam thermal power plant is a large and complex thermodynamic system based on the Rankine cycle. Chemical energy from coal is used to convert water into high pressure superheated steam by means of a steam boiler sub-system. Superheated steam at high pressure feeds into the turbine sub-systems to convert pressure energy into mechanical energy (i.e. shaft work), which is then transformed into electrical power by a generator sub-system. Spent steam from the turbine sub-system is condensed by a condenser sub-system. The condensate, along with makeup water, is collected and pumped back into the steam boiler using a condensate extraction pump and feed pump sub-system to complete the cycle. The entire system consists of six sub-systems.

1. The steam boiler sub-system is used without a standby sub-system, and is denoted by 'S', failure of which leads to system failure.
2. The turbine sub-system is denoted by T, which is one sub-system.
3. The condenser sub-system, C, is a single sub-system.
4. The condensate extraction pump sub-system (P_h), which has a total of n_{ph} sub-systems, of which two are in operation (active sub-systems), while the rest do not take part in the operation and are kept as passive sub-systems. System failure takes place when two sub-systems fail simultaneously.
5. The feed pump sub-system (P_b) consists of a total of n_{pb} sub-systems, two of which are active while the rest are standby sub-systems. The system fails only when two sub-systems fail in succession.
6. The generator sub-system is denoted by 'G' and consists of one sub-system, failure of which leads to system breakdown.

3. PERFORMANCE EVALUATION MODEL

The performance evaluation model for a thermal power plant has been developed to predict the operational availability of the system. The failure and repair rates of the different subsystems are used as standard input information for the module. The flow of states for the system under consideration is described in a state transition diagram (Figure 1), which is a logical representation of all the possible states' probabilities that might be encountered in failure analysis of the steam thermal power plant. Formulation is carried out using the joint probability functions based on the transition diagram. The probabilities are mutually exclusive, and provide scope to implement a Markovian approach for availability analysis of the power generation process [1-5].

The following assumptions are made:

a) At any given time the system is either in an operating state or in a failed state.
b) Failure and repair rates are constant and statistically independent.
c) A repaired sub-system is as good as new.
d) Standby sub-systems are of the same nature and capacity as active sub-systems.
e) Repair facilities are always available.

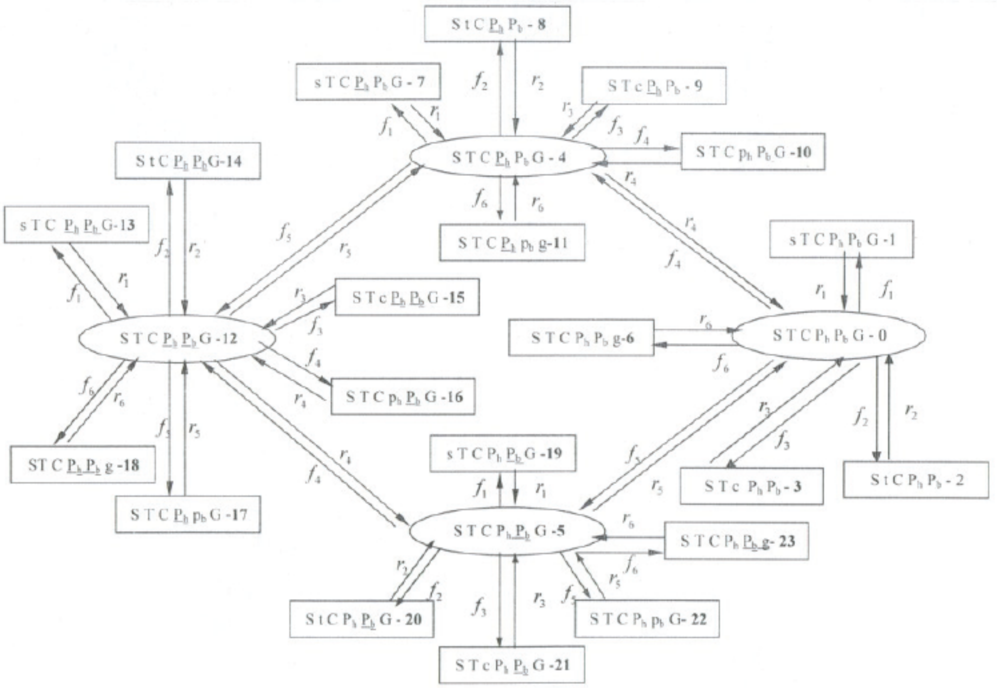

Figure 1: Transition diagram of the system
Small alphabets showing failure state of the individual components

Considering constant failures and repair rates, the mathematical formulation is done using the probabilistic Markov birth-death approach. The difference differential equations are developed for each state in the transition diagram (Figure 1) following Sharma and Tewari [9] as:

For state 0:

$$P_0(t+\Delta t) = (1-\lambda_1\Delta t-\lambda_2\Delta t-\lambda_3\Delta t-\lambda_4\Delta t-\lambda_5\Delta t\ -\lambda\Delta t)P_0(t)+\alpha_1\Delta tP_1(t)+\alpha_2\Delta tP_2(t)$$
$$+\alpha_3\Delta tP_3(t)+\alpha_4\Delta tP_4(t)+\alpha_5\Delta tP_5(t)+\alpha_6\Delta tP_6(t) \quad (1)$$

$$\text{using} \left(\frac{P_0(t+\Delta t)-P_0(t)}{\Delta t}\right)_{\lim\ \Delta t\to 0} = P_0(t) \quad (2)$$

$$\text{or } P_0(t)+(\lambda_1+\lambda_2+\lambda_3+\lambda_4\Delta t+\lambda_5\Delta t+\lambda_6)P_0(t)=1+\alpha_1P_1(t)+\alpha_2P_2(t)\ +\alpha_3P_3(t)+\alpha_4P_4(t)\ +\alpha_5P_5(t)+\alpha_6P_6(t) \quad (3)$$

Similarly for state 4, 5, and so forth.

$$P_4(t)+(\lambda_1+\lambda_2+\lambda_3+\lambda_4\Delta t+\lambda_5\Delta t+\lambda_6+\alpha_4)P_4(t)\ =\alpha_1P_7(t)+\alpha_2P_8(t)\ +\alpha_3P_9(t)+\lambda_4P_0(t)+\alpha_4P_{10}(t)$$
$$+\alpha_5P_{12}(t)+\alpha_5P_{11}(t) \quad (4)$$

$$P_5'(t) + (\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4\Delta t + \lambda_5\Delta t + \lambda_6 + \alpha_5)P_5(t) = \alpha_1 P_{19}(t) + \alpha_2 P_{20}(t) + \alpha_3 P_{21}(t) + \alpha_5 P_{22}(t) + \alpha_6 P_{23}(t) + \alpha_4 P_{12}(t) + \lambda_5 P_0(t) \quad (5)$$

$$P_{12}'(t) + (\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4\Delta t + \lambda_5\Delta t + \lambda_6 + \alpha_4 + \alpha_5)P_{12}(t) = \alpha_1 P_{13}(t) + \lambda_5 P_4(t) + \alpha_2 P_{14}(t) + \alpha_3 P_{15}(t) + \alpha_4 P_{16}(t) + \lambda_4 P_5(t) + \alpha_5 P_{17}(t) + \alpha_6 P_{18}(t) \quad (6)$$

$P_J'(t) + \alpha_1 P_J(t) = \lambda_1 P_J(t)$; J=1, 7, 13 and 19 (7)

$P_J'(t) + \alpha_2 P_J(t) = \lambda_2 P_J(t)$; J=2, 8, 14 and 20 (8)

$P_J'(t) + \alpha_3 P_J(t) = \lambda_3 P_J(t)$; J=3, 9, 15 and 21 (9)

$P_J'(t) + \alpha_4 P_J(t) = \lambda_4 P_J(t)$; J=10 and 16 (10)

$P_J'(t) + \alpha_5 P_J(t) = \lambda_5 P_J(t)$; J=17 and 22 (11)

$P_J'(t) + \alpha_6 P_J(t) = \lambda_6 P_J(t)$; J=6, 11, 18 and 23 (12)

These differential equations (3)-(12) are solved using the Laplace Transformation (LT) technique for given initial and boundary conditions. Taking LT and solving these in terms of $P_0(s)$ as:

$P_i = C_i(s)P_0(s)$;for I = 1 to 23 (13)

The constants C_i used in equation (13) are given in Appendix A.
Using the normalizing condition, we get:

$$P_0(s) = \frac{1}{1 + \sum_{i=1}^{i=23} C_i} \quad (14)$$

Hence, operational availability of the system can be obtained by adding the probabilities of successful states, as shown in the transition diagram (Figure 1).

$$Av(s) = \left(1 + C_4(s) + C_5(s) + C_{12}(s)\right)P_0(s) \quad 15)$$

The Laplace inverse and initial conditions are $P_0(0)$ = 1, otherwise = 0. Since the plant is required to run for extended times (t ⇒ ∞ or s ⇒ 0), thus the steady state availability of the system may be written as:

$$Av. = \left(1 + C_4(0) + C_5(0) + C_{12}(0)\right)P_0 \quad (16)$$

4. ECONOMIC EVALUATION MODULE

The economic analysis of the plant has been carried out on the basis of initial capital investment (CI_T, €), operating cost (CO_y, €/yr), and annual revenue obtained (CR_y, €/yr). The plant net value or profitability P_F has been evaluated following Caputo *et al* [7]. Thus the total initial capital investment can be written in terms of individual equipment/component cost as:

$$CI_T = f\left(CI_S + CI_T + CI_C + n_{Ph} CI_{Ph} + n_{Pb} CI_{Pb} + CI_G\right) \quad (17)$$

Here f is a factor accounting for the cost of direct installation, auxiliary, instrumentation and control, engineering and plant start-up. Caputo *et al* [7] have fixed f at 1.87. However, the cost of piping, civil work, and electrical fitting has been neglected. The costs of initial capital investment for each equipment/sub-system of the thermal power plant have been obtained from the literature, using the relation in the form of $CI = a\, M_W^b$. The values of constants a and b are given in Table 1.

Total operating cost is obtained on an annual basis, including the operating labour cost (CO_L, €/yr), fuel purchased cost (CO_F, €/yr), maintenance cost (CO_{repair}, €/yr), insurance and general cost (CO_{insgen}, €/yr). The fuel transportation cost has been left out of consideration in the present work.

Equipment	A	b
Steam boiler (S)	1340000	0.694
Turbine (T)	633000	0.398
Condenser (C)	398000	0.333
Condensate extraction pump (P_h)	9000	0.4425
Feed pump (P_b)	35000	0.6107
Generator (G)	138300	0.3139

Table 1: Constants for cost estimation (Caputo *et al* [7])

$$CO_y = CO_L + CO_F + CO_{repair} + CO_{insgen} \quad (17a)$$

$$= n_L C_{PL} + m_F C_F + 0.03 CI_T + 0.025 CI_T \quad (17b)$$

Here n_L denotes the personnel employed on an annual basis (varies 12~16) at a personnel average income of 26 €/yr [7]. The repair or maintenance cost is taken as 3% of total capital investment.

If the overall thermal efficiency of the plant (η_{ov}) is ~20%[8], the annual fuel consumption has been calculated in terms of the heating value of fuel as:

$$m_F = \frac{M_W \times 3600 \times hr_{up}}{\eta_{ov} lhv_F} \quad (18a)$$

The annual operating plant period (hours) in which the plant is in an up-state can be obtained from the definition of plant availability as:

$$Av. = \frac{hr_{up}}{24 \times 12 \times 30} \quad (18b)$$

Here *Av.* is the steady state availability of the plant, which has been obtained from equation (16). Annual revenue obtained from the generated electricity has been evaluated as:

$$CR_y = f_{auxil} M_W hr_{up} C_{EP} \quad (19)$$

f_{auxil} accounts for the energy needs of auxiliary pieces of equipment, and C_{EP} is the current market price of electricity (~103 € /M_W)[7].

Finally, the objective function is formulated to maximize the profit index P_F as:

$$P_F = \sum_{k=1}^{ny} \frac{\left(CR_y - CO_y\right)_k}{(1+dr)^k} - CI_T \quad (20)$$

Here *dr* and *ny* are the discount rate and power plant life respectively. Here the discount rate is fixed at 9 % [7].

5. RESULTS AND DISCUSSION

The performance evaluation model is used to predict the steady-state availability of the thermal plant for known input values of failure and repair rates of its components. From the maintenance sheet of the steam/water cycle of a particular thermal power plant (Panipat), and through discussions with plant personnel, appropriate failure and repair rates of steam turbine, condenser, condensate extraction pump, feed pump and generator sub-systems are obtained and assigned failure rate values of 0.0025, 0.005, 0.005, 0.0025, 0.0025, 0.0005 failures/hr respectively, while the repair rates are fixed at 0.1 repairs/hr for each component in the system. With these values, the effects of failure and repair rates of various sub-systems on the operational availability of the components and the system as a whole are shown in Figures 2 to 4. Figure 2 shows the effect of failure and repair rates of the steam boiler sub-system (without any standby) on system availability. It can be observed from the figures that the operational availability of the system decreases exponentially from 0.9 to 0.47 for a variation in failure rate from 0 to 0.03 failures/hr at a typical repair rate of 0.03 repairs/hr. With a further increase in the repair rate of the steam boiler system, the availability of the operation also improves (Figure 2).

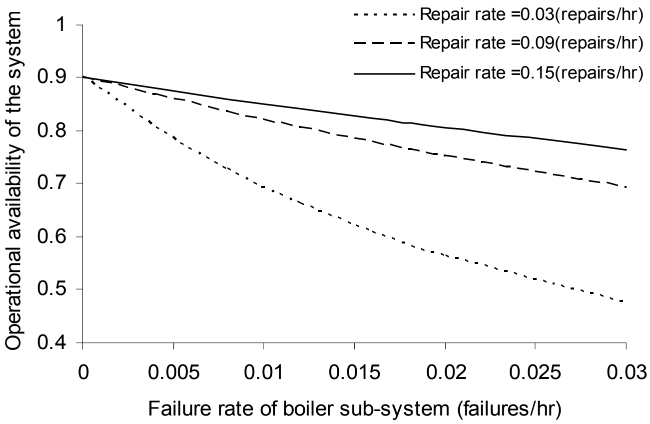

Figure 2: Effect of failure and repair rates of the steam boiler sub-system on the operational availability of the system

Results for the limiting case of the steam boiler system, which corresponds to a single component (without a standby component) are shown in Figure 3. As expected, the operational availability of the steam boiler system improves by increasing repair rates and by reducing the failure rate of the steam boiler system. Comparing the predictions for the single component system (Figure 3) and the overall system (Figure 2), it can be observed that for the single component the variations in availability figures are greater than for the overall system. Likewise, the effect of failure and repair rates of the condensate extraction pump sub-system on overall system availability is shown in Figure 4. The variation in operational availability is found to be less sensitive to failure and repair rates in the case of the condensate extraction pump system (single standby component).

From the above studies, the variation in the operational availability of the overall systems is found to be less sensitive when compared with a single component. Moreover, for system components with large numbers of standby sub-systems, the variations in operational availability are also less.

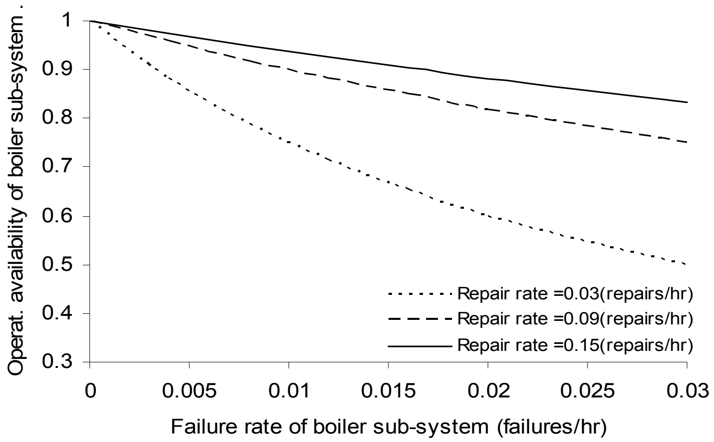

Figure 3: Effect of failure and repair rates on steam boiler availability.

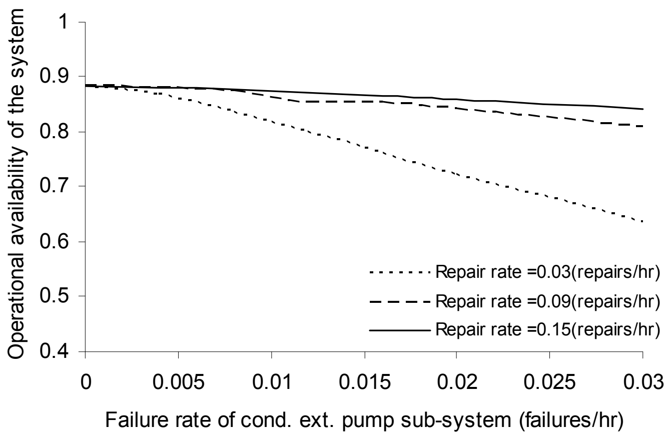

Figure 4: Effect of failure and repair rates of condensate extraction pump sub-system on operational availability of the system

The economic evaluation module developed above has been used to predict total capital investment, total operating costs, and annual revenues earned from energy sales and net present value for known input information of operational availability figures, component cost correlations, and numbers of sub-systems (active and passive). Parametric analysis is carried out to investigate the effect of system availability, plant capacity, sub-systems of condensate extraction pump and feed pump sub-systems on total capital investment, annual operating cost, annual revenue earned, and net present value, as shown in Figures 5 to 8. Figure 5 shows that the annual revenue earned, annual operating cost and net present value improve with system availability. The improvement in the net present value index and annual revenue earned is significant, compared with the annual operating cost and total capital investment cost for a typical plant capacity of 5MW.

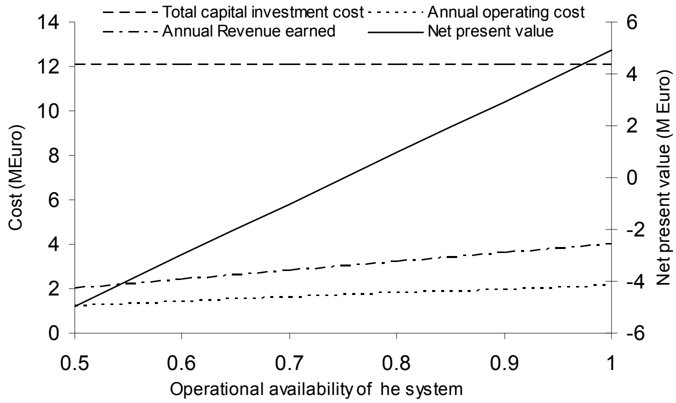

Figure 5: Effect of system availability on total capital investment, annual operating cost, annual revenue earned, and net present value

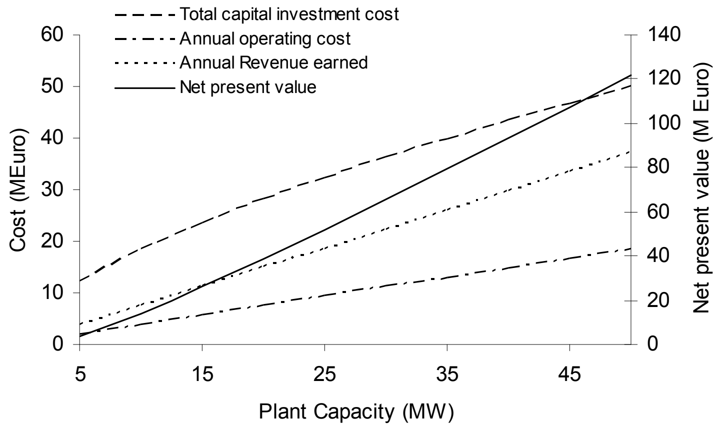

Figure 6: Effect of plant capacity on total capital investment, annual operating cost, annual revenue earned and profitability index

Figure 6 shows the effect of plant capacity on total capital investment, annual operating cost, annual revenue earned, and net present value. The figure reflects a sharp improvement in the annual revenue and net present value index. Although the total capital investment cost and annual operating cost also increase, the increase is not as significant as in the case of annual revenue cost. The graph also shows that the profitability index improves steeply with increased plant capacity at a typical availability level of 0.93.

The effect of using higher order standby sub-systems for the condensate extraction pump and feed pump sub-systems has also been investigated, as shown in Figures 7 and 8. The figures reflect that initial capital investment costs increase, while the profitability index decreases with the addition of passive sub-systems to the system at the fixed availability level of 0.8. The effect of increasing passive sub-systems of the condensate extraction pump on net present value is comparatively higher when compared with the case of the feed pump sub-system. It is due to the fact that the initial capital investment cost of a single condensate extraction pump sub-system is higher, compared with the initial capital investment cost of the feed water pump.

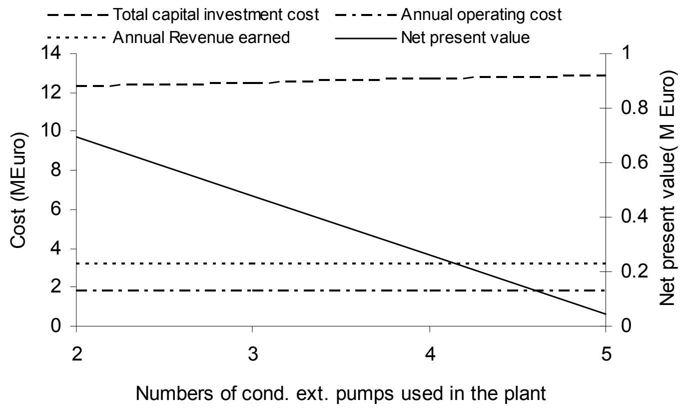

Figure 7: Effect of n_{ph} on total capital investment, annual operating cost, annual revenue, and profitability index

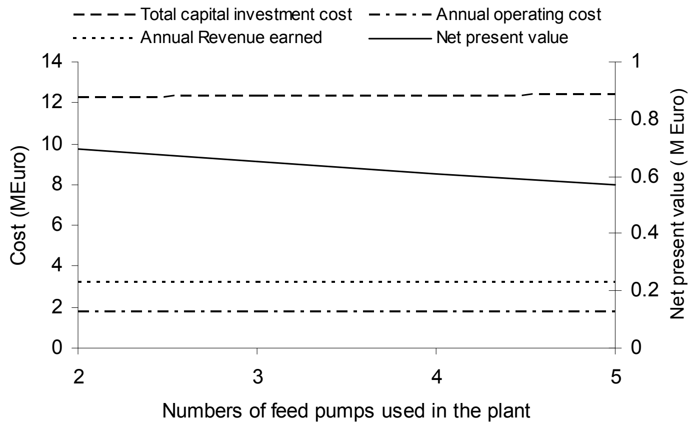

Figure 8: Effect of n_{pb} on total capital investment, annual operating cost, annual revenue earned, and profitability index

A performance evaluation and economic analysis model has been used to predict the effect of the repair rate of various sub-systems on operational availability, annual operating cost, annual revenue earned, and net present value. Repair facilities for all components are considered to be the same and are assigned as α= 0.1 (repairs/hr); while the failure rates are fixed at $\lambda_1=\lambda_4=\lambda_4=0.0025$, $\lambda_2=\lambda_3=0.005$, and $\lambda_6=0.005$ respectively. With these baseline values and a plant life of 20 years operating at 5MW without any standby sub-systems, the simulations are performed to predict the effect of the repair rate of the steam boiler, the condensate extraction pump, and the generator on operational availability, annual operating cost, total capital investment, and net present value, as shown in Figures 9 to 11.

Figure 9 illustrates the variation in the operational availability, annual operating cost, annual revenue earned, and net present value index as a function of repair rate of boiler α_1. The sharp improvements in operational availability, net present value index, and annual revenue earned are observed for an initial increase in the repair rate to the critical value of 0.025 repair/hr; thereafter they do not show any significant variation for a further increase in the repair rate. Figures 10 and 11 show similar trends. However, the critical repair rate conditions for the condensate extraction pump and generator sub-system are identified at 0.025 and 0.05 respectively. Below these critical repair rates the operational availability

decreases sharply, while beyond these conditions, the plant availability, net present value, and annual revenue earned are found to be insensitive to the repair rates.
The dependence of the repair rate on the net present value index, annual revenue earned, and annual operating cost is understandable, since the repair rates depend on availability (Figures 2 to 4), and availability relates to the various costs (Figure 5). Simulation also shows that the initial capital investment cost for the present plant case is maintained at 12.34 M€.

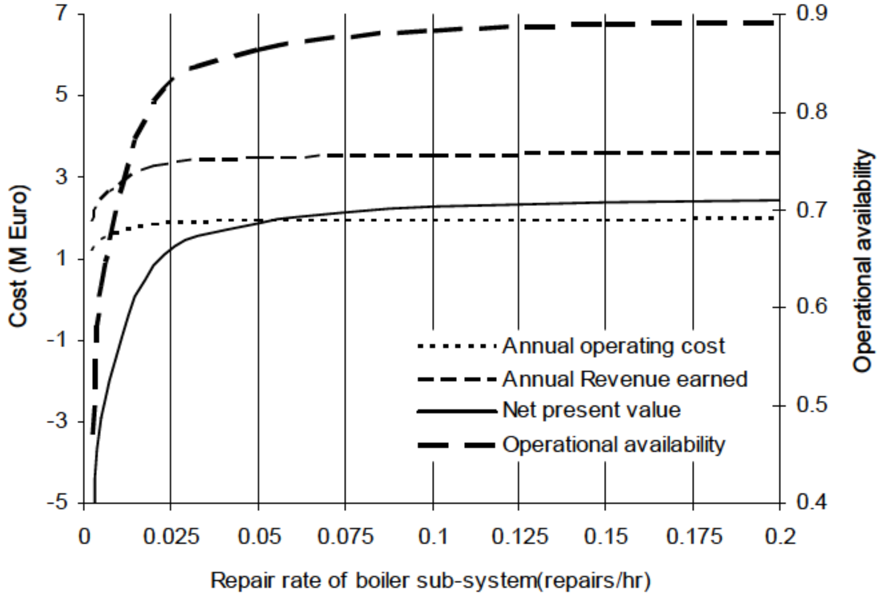

Figure 9: Effect of repair rate (steam boiler sub-system) on operational availability, annual operating cost, annual revenue earned, and net present value

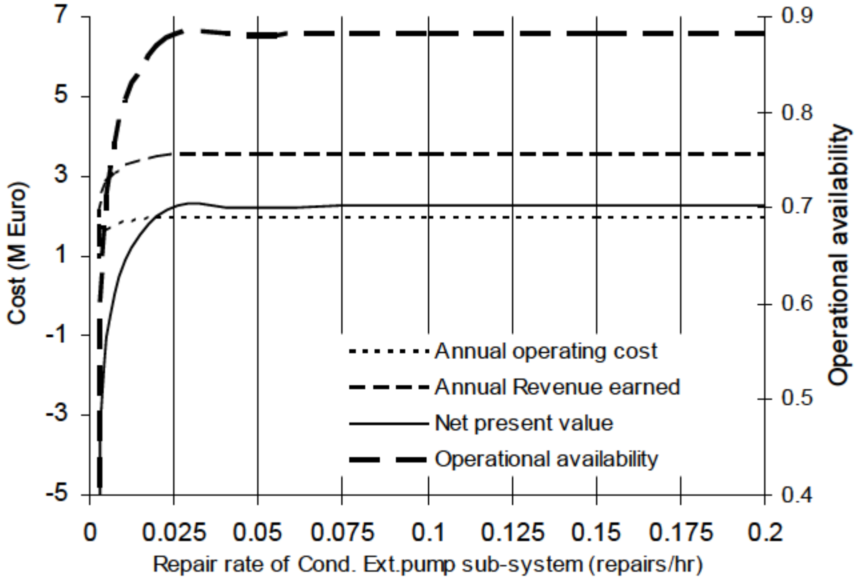

Figure 10: Effect of repair rate (condensate extraction pump sub-system) on operational availability, annual operating cost, annual revenue earned, and net present value

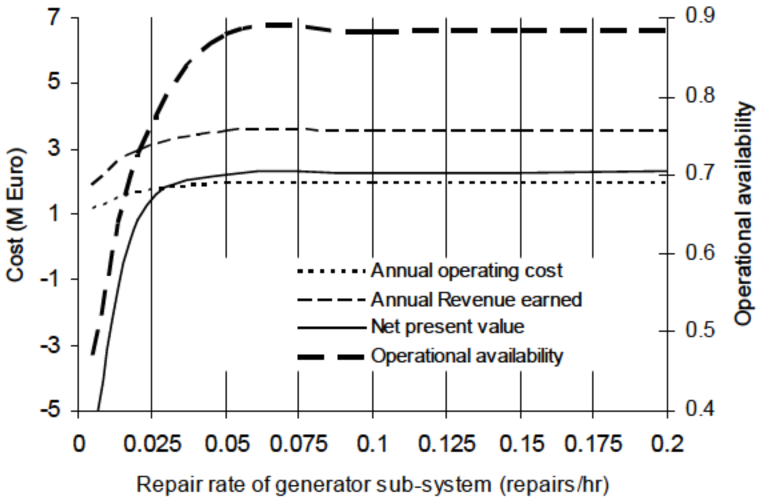

Figure 11: Effect of repair rate of generator on operational availability, annual operating cost, annual revenue earned, and net present value.

In the above analysis, the initial cost of coal conveyors and the cooling tower sub-system has not been considered. It is assumed that sufficient river water is available for cooling applications, and that refined and crushed coal is readily available for the present use.

6. CONCLUSIONS

A performance evaluation and economic analysis model for a thermal power plant is presented to predict operational availability, annual operating cost, total capital investment cost, and net present value. A parametric analysis of the performance evaluation model is carried out to investigate the effect of failure rates and repair rates. The operational availability figures are found to improve with increasing repair rates and diminishing failure rates for different sub-systems. The failure and repair rates are also found to be less sensitive in the plant having components with more redundancies, compared with components having fewer redundancies.

An economic analysis model is also used to study the effect of availability, plant capacity, and numbers of sub-systems of n_{Ph} and n_{Pb} on the total capital investment, annual operating cost, annual revenue earned, and net present value. The model shows that plant operational availability and power generation capacity are sensitive, while n_{Ph} and n_{Pb} influences the net present value less. Predictions of reliability and the economic evaluation model predict a critical condition for repair rate in the range from 0.025 to 0.05 repairs/hr. Within this critical repair rate range, operational availability decreases sharply. However, beyond this condition the plant availability, net present value, and annual revenue earned are insensitive to the repair rate.

A large number of failures occur mainly because of improper design and overstressing of critical components, which can be avoided by introducing properly designed components at optimum in-built performance figures. Advanced maintenance planning should be available for the steam boiler, turbine, condenser, and generator, as these are identified as critical components of thermal power plants if unnecessary delays in the execution of preventive and corrective maintenance actions are to be avoided. Since the critical components involve large capital implications, the higher in-built performance figure should be recommended to meet the requirement of failure-free operation for a lengthy period. Adequate repair facilities, spare parts, and skilled manpower should be available to optimize the repair rates of various sub-systems (repair rate ≥0.05 for the present case). Failure and repair rates of various components, along with human performance factors, should also be optimized to accomplish the set goals of long-run availability and the economical generation of electrical power.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

[1] **Govil, A.K.,** 1983. *Reliability engineering,* Tata McGraw-Hill Publishing Company Ltd.

[2] **Shrinath, L.S.,** 1991. A test book on reliability engineering, 3rd ed., Affiliated East-West Press Ltd.

[3] **Sharma, Avdhesh Kr.,** 1994. Reliability analysis of various complex systems in thermal power station. M. Tech, thesis, Kurukshetra University (REC Kurukshetra), Haryana, India.

[4] **Dhillon, B.S.,** 1999. *Design reliability fundamentals and applications,* CRC Press LLC.

[5] **Rao, S.S.**, 1992. *Reliability-based design,* McGraw Hill, Inc.

[6] **Singhal A.K., Jain S.**, 2005. Reliability analysis and risk assessment of a steam power plant using mixed redundancy, in *Proc 14th ISME Int. Con. on Mech Eng in Knowledge Age,* DCE, Delhi, India, 2005, pp 556-560.

[7] **Caputo, C.A., Palumbo, M., Pelagagge, P.M., and Scacchia, F.,** 2005. Economics of biomass energy utilization in combustio*n and gasification plants: Effect of logic variables, Biomass and Bioenergy*, 28, pp 35-51.

[8] **Li, W. Kam and Priddy, A., Paul,** 1985. *Power plant system design*, John Wiley & Sons.

[9] **Avdhesh Kr. Sharma, and P.C. Tewari,** 2004. Reliability modeling for the feed water-steam c*ircuit in thermal pow*er plant, in: *Proc of Int. Conf. on 'Energy and Environment – Strategies for Sustainable Development*', Jamia Millia Islamia, Delhi, India, Jan 23-24, 2004, pp 20-26

[10] **Avdhesh Kr. Sharma, and P.C. Tewari,** 2007. "Performance Modeling and Decision Support System of Feed Water Unit of a Thermal Power Plant" in *Int. Conf.* on *'Modeling and Simulation', Coimbatore*, India, Aug 27-28, 2007.

[11] **Sorabh Gupta, P.C. Tewari and Avdhesh Kr. Sharma ,** 2008. "Performance Modeling and Behavior Analysis of Coal Handling System of a Thermal Power Plant" at '*Multi Disciplinary Engineering Technologies', Bharti Vidyapeeth's College of Engineering, New Delhi, Vol. 3, No.1, pp.1-9, July- Dec., 2008.*

APPENDIX A

$$C_i(s) = \frac{\lambda_i}{s + \alpha_i} \text{ ; i=1,2,3,6} \quad \text{(i)}$$

$$S_i = \frac{\alpha_i \lambda_i}{s + \alpha_i} \text{ ; i=1,2,..6} \quad \text{(ii)}$$

$$C_4(s) = \frac{\lambda_4 + \alpha_5}{s + D_1(s)} \quad \text{(iii)}$$

$$D_1(s) = \sum \lambda_i + \alpha_4 - S_1(s) - S_2(s) - S_3 - S_4(s) - S_6(s) \quad \text{(iv)}$$

$$C_5(s) = \frac{\lambda_5 + \alpha_4}{s + D_2(s)} \quad \text{(v)}$$

$$D_2(s) = \sum \lambda_i - \lambda_5 + \alpha_4 - S_1(s) - S_2(s) - S_3 - S_5(s) - S_6(s) \quad \text{(vi)}$$

$$C_7(s) = C_1(s)C_4(s) \quad \text{(vii)}$$

$$C_8(s) = C_2(s)C_4(s) \quad \text{(viii)}$$

$$C_9(s) = C_3(s)C_4(s) \quad \text{(ix)}$$

$$C_{10}(s) = \frac{\lambda_4}{s + \alpha_4} C_4(s) \quad \text{(x)}$$

$$C_{11}(s) = C_6(s)C_4(s) \quad \text{(xi)}$$

$$C_{12}(s) = \frac{\frac{\lambda_5 \lambda_4}{s + D_1(s)} + \frac{\lambda_4 \alpha_4}{s + D_2(s)}}{1 - \frac{\lambda_5 \alpha_5}{s + D_1(s)} - \frac{\lambda_4 \alpha_4}{s + D_2(s)}} \quad \text{(xii)}$$

$$C_{13}(s) = C_1(s)C_{12}(s) \quad \text{(xiii)}$$

$$C_{14}(s) = C_2(s)C_{12}(s) \quad \text{(xiv)}$$

$$C_{15}(s) = C_3(s)C_{12}(s) \quad \text{(xv)}$$

$$C_{16}(s) = \frac{\lambda_4}{s + \alpha_4} C_{12}(s) \quad \text{(xvi)}$$

$$C_{17}(s) = \frac{\lambda_5}{s + \alpha_5} C_{12}(s) \quad \text{(xvii)}$$

$$C_{18}(s) = C_6(s)C_{12}(s) \quad \text{(xviii)}$$

$$C_{19}(s) = C_1(s)C_5(s) \quad \text{(xix)}$$

$$r_2 \quad \text{(xx)}$$

$$C_{21}(s) = C_3(s)C_5(s) \quad \text{(xxi)}$$

$$C_{22}(s) = \frac{\lambda_5}{s + \alpha_5} C_5(s) \quad \text{(xxii)}$$

$$C_{23}(s) = C_6(s)C_5(s) \quad \text{(xxiii)}$$