Development of Reliability-Based Decision Making for Optimum Operation and Maintenance Strategy in Coal-Fired Power Plant

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Abstract. Operation and Maintenance (O&M) held a significant factor in the power generation business. Despite the costs only about 15% of all life cycle costs, this figure may fluctuate to ± 20% due to spare part costs, equipment's economic lifetime, and personnel cost. This paper describes a reliability-based Decision Support System (DSS) development to determine an optimum O&M strategy for coal-fired power plants. The methodology was developed from System Dynamics modeling, with the objective function to maximize Net Present Value (NPV) and maintain availability exceeding its goal. DSS allows users to study the power plant cost characteristics within their life cycle, including its sensitivity to NPV. The model was tested to a 600 MW coal-fired power plant in Indonesia. Mean Absolute Percentage Error (MAPE) applied as model acceptance criteria. From this study, coal price was the most sensitive variable to NPV (62.36%), followed by dispatcher demand (53.31%), and overhaul duration (1.5%). From 4 simulated scenarios, it was concluded that O&M outsourcing as asset operator authority was a proper choice that provides the highest NPV. Nevertheless, some risks related to employee competence and bureaucratic obstacles should be controlled.

1. Introduction

The Indonesian government continues to raise the electrification ratio in Indonesia, through sales growth planning, power generation, transmission, and distribution development project. Power plant projects should adhere to the lowest production cost with higher reliability. The lowest cost achieved by minimizing Net Present Value (NPV) along the entire lifecycle, such as investment costs, fuel costs, operating and maintenance costs, and energy costs not served. Power plant reliability is measured by Load Loss Probability (LOLP) and power reserves [1].

A crucial factor in power generation business is related to Operation and Maintenance (O&M). Though O&M costs are only around 15% of the entire life cycle cost, this figure can fluctuate up to 20% due to spare parts costs, economic age of equipment, and staffing costs. For this reason, optimizing O&M cost is the right step to provide cheap and quality electricity [2]. A strategy to minimize O&M is outsourcing this process to third party companies. Fill and Visser said power plant owners outsource their O&M for three main reasons: cost reduction, employment strategy for non-core areas, and also risk management [3].
The outsourcing definition was referred to as Hiemstra and Van Tilburg who introduce the non-capacity outsourcing concept. If capacity outsourcing is defined as a service that widely used by companies to provide additional capacity for special seasons or peak demand periods, then non-capacity means that suppliers take over some of the company’s value in long-term contract periods [3].

Kulkarni, et al. also explained four outsourcing models that were classified based on the scope of their work. There were: (1) maintenance outsourcing, (2) basic O&M outsourcing, (3) enhanced O&M outsourcing, and (4) 100% outsourcing including capital spares. The paper also distinguished the scope of work and authority between the asset owner and asset operator [4].

Mercer researched on the decision making about power plant O&M services. There are several alternatives to optimized O&M management of the research: (1) all work scopes are internal, (2) outsourcing for configuration maintenance and major maintenance, (3) outsourcing for configuration maintenance, major maintenance, and operation support, (4) outsourcing for all types of maintenance and operational support, (5) full operation and maintenance. Mercer used the Analytical Hierarchy Process (AHP) for optimized each option [3].

Nevertheless, many experts criticized AHP as a decision-making tool. Hart Witch said that AHP does not provide a standard guide to the structure of the problems that must be resolved [5]. This technique also has limitations on the formation of hierarchy, criteria, alternatives, and mechanisms of aggregation of opinion, especially if among experts constrained geographical distance and time.

The AHP method cannot respond to change conditions at longer time frames. Research on the generation of electricity on short or medium-term models has been widely implemented [6] but long term models are still areas that have not been widely explored [7].

System dynamics developed by Prof. Jay W Forrester from the Massachusetts Institute of Technology (MIT). Initially, systems dynamics were used in management and engineering science but gradually developed into tools for social analysis, economics, physics, chemistry, biology, and ecological systems [8].

System thinking method has been widely used for 30 years [9]. This concept an effective tool to understood large-scale complex management. System dynamics were designed based on systems thinking with an established methodology for learning and managing complex feedback systems. Unique circular diagrams, causal loops, or stock-flow diagrams were needed to build a system dynamic model.

Kang used system dynamics to analyze reliability and risk quantitatively as a time function of the nuclear power plant in South Korea. This research was able to determine safe and low risk Limiting Conditions for Operations (LCOs) of nuclear plants. CLD was used to calculate impacts. While the frequency of failures was obtained from the simulation. It would very important to determine the probability of risk [10].

As explained before, modeling for power generation O&M service was a simultaneous multivariable operation. It should be analyzed in a long-term period thus the accurate decision was achieved. Hence, system dynamics were expected to answer those needs.

The National Electric Power Supply Company Association determined the electricity business process. It divided into 4 categories: asset owner, asset manager, and asset operator [11]. Furthermore, there are several options for managing a power generation company, that commonly applied in Indonesia. The methods are: (1) O&M is undertaken by asset owners themselves; (2) O&M is outsourced to a third-party company as an asset manager; (3) O&M is outsourced within the authority as asset operator; or (4) partially outsourcing for certain equipment.

Decision making on those 4 options was a challenging topic because involving simultaneous multi variables and running within a long-term contract period. A comprehensive Decision Support System (DSS) would help the CEO determine the most profitable business strategy.

Some importance assumptions in this study were: (1) the model was compatible for pulverized coal-fired power plant above 300 MW; (2) the analyzed cost structure was limited to Operation and Maintenance (O&M) phase, while acquisition and disposal costs were carried out under a different
funding scheme; (3) reliability analyzed in the useful life period; (4) researcher was positioned as an asset owner.

This study aimed to create a model to optimize several options O&M strategies used in managing coal fire plants therefore they can provide maximum benefits. Some influential variables were modeled using system dynamics method with an objective function to maximize profit and reliability. In a longterm period, reliability was often expressed in availability. The novelty of this paper was reliability-based modeling, therefore Decision Support System (DSS) represents power generation characteristics along their whole life cycle.

2. Methods

A system dynamics approach was very useful for conceptualizing complex systems, which involve human interaction and other factors. Systems dynamics have been widely used in research related to electricity generation, and supporting equipment. Provided a flexible method, system dynamics applications were usually related to plant operations surrounded other aspects such as economic or social studies. Besides, it was very useful for long term studies [12].

Causal Loop Diagrams (CLD) was used to reduce the complexity and to prioritize a conceptual model of the system studied. Stock-flow diagrams were usually developed based on causal loop diagrams and visualized through professional software for quantitative simulations and analyzes. Before the model can be quantitatively analyzed, it was important to build trust in it. Therefore, a series of tests has been suggested for validating a system dynamic model [13].

CLD was established by many variables in which variables relationships were marked by arrows. Arrows with a positive sign (+) indicate a change in the variable at the arrow-tail leads to a change in the variable at the arrowhead in the same direction. Arrows with a negative (−) sign indicate a change in the arrow-tail variable leads to an inverse change in the arrowhead variable (opposite direction). R- Reinforcing loop, the result of which is an amplification of the initial pattern of behavior. B-Balancing loop, the result of which may be to dampen the initial pattern of behavior or create oscillation [14].

The basic structures of computerized system dynamics were formulated as:

\[
\frac{d}{dt}X(t) = f(X,P)
\]

where:
- X : Level vector (stock or state variable)
- P : Set parameter
- F : Non-linear vector function

The research methodology of this paper referred to the block diagram in Figure 1. Research started with system dynamics model development. The model was developed from a power generation technical/economic map proposed by the Electrical Power Research Institute as part of the Risk-Informed Asset Management (RIAM) program [15]. This research used Vensim, a Ventana’s famous System Dynamics software, to build up a model.

Because an O&M contract is usually dedicated for a long period, the profit was expressed in Net Present Value (NPV). According to the Life Cycle Cost (LCC) cycle, the simulation was limited only to the O&M phase.

A Causal Loop Diagram (CLD) was constructed to map the causal relationships of several parameters, thus translated into stock and flow diagrams to facilitate the formulation. Existing formulas put into the model so that the model was ready to be simulated.

Data for simulations were taken or proceed from several references, including but not limited to: power plant reports, corporate documents, electricity commercial regulation, the international standard, IT database, external data, and expert judgment.

In the asset management view, costs are evaluated for the whole asset life cycle. The Institute of Asset Management described an asset management landscape where the life cycle consists of (1) acquisition, (2) operation, (3) maintenance, and (4) disposal phases [16]. A cost structure during the
life cycle named risk cost, where the value is likely. Then the reliability parameters were needed to quantify.

Dhillon defined reliability as the probability that an item will perform its assigned mission satisfactorily for the stated period according to the specified conditions. This is an important factor in asset management because of the lower the reliability, the equipment will require high maintenance [17].

\[ R(t) = 1 - F(t) = 1 - \int_0^t f(t)dt \] (2)

where:
- \( R(t) \) : Reliability – time function
- \( F(t) \) : Cumulative distribution function
- \( f(t) \) : Failure density function

Figure 1. Research Method
Mean Time to Failure (MTTF) is the average time when equipment is reliable. TTF is calculated from the deviation between downtime at time t with uptime at time t-1 for the same equipment. Mean Time to Repair (MTTR) represents the time needed to complete maintenance activities [17]. If availability was defined as the probability that an item is available for use when required, thus availability for system m along period t, expressed as:

$$UA_m = \frac{MTTF_m}{MTTF_m + MTTR_m}$$

(3)

The reliability parameter, R(t), was obtained through modeling. Downtime data was simulated by Minitab software after the Reliability Block Diagram (RBD) was determined. Its reliability focused on main and supporting equipment than aggregate to plant level in serial logic. In the long term, reliability at the plant level usually stated in availability.

Models were verified through several processes: logical checking, model structure checking, unit model checking, and model sensitivity analysis. Related to the sensitivity test, a wide range of data were tested to the model, then evaluated whether the model provided a sensitive response. The verification process utilized features provided by Vensim software.

The model was simulated based on a 600 MW coal-fired power plant data. The result was compared to the reference data. Mean Absolute Percentage Error (MAPE) method was applied to test model accuracy. MAPE was calculated by the equation:

$$MAPE = \frac{1}{n} \sum_{i=1}^{n} \frac{|X_m - X_d|}{X_d} \times 100\%$$

(4)

Where MAPE was Mean Absolute Percentage Error (%), Xm was simulation result, Xd was actual data, n was the number of data. The acceptance criteria were: MAPE < 10% called highly accurate forecasting, 10% < MAPE < 20% is good forecasting, 20% < MAPE < 50% is reasonable forecasting, more than 50% is weak and inaccurate [18].

Figure 2 describes the Causal Loop Diagram (CLD) for the power generation model. Net cash flow calculated by revenue and life cycle costs. The higher revenue, net cash flow would increase as well. Conversely, life cycle costs contributed to net cash flow negatively. This correlation formed a balanced feedback loop (1).

Availability and energy produced would contribute to revenue. Those factors were strongly influenced by availability factors, technical requirements in Power Purchase Agreement (PPA), and energy demand from The Dispatcher. Availability was within the asset owner’s control, but energy demand was exogenous.

The planned outage, unplanned outage, and derating would reduce availability. Besides, planned outage, unplanned outage, and derating would affect proactive maintenance and reactive maintenance cost. High reliability also had a positive impact on availability. The relationship between reliability, availability, and outage/derating formed a reinforced feedback loop (4).

From several factors above, reliability was the most sensitive to others. If reliability was high, availability will increase, leading to a revenue increase. On the other hand, high reliability would suppress reactive maintenance costs, which also contributes positively to net cash flow. Reliability did not impact on other factors directly, but there was some delay. Reliability is also determined by an exogenous factor such as machines or management factors (people, methods, tools, etc). Due to outsourcing policies, well managed O&M would improve equipment reliability. Adequacy of maintenance budget also improved plant reliability. This condition provided a reinforced feedback loop (2). Since this study did not vary the power plant types, reliability was controlled by the equipment.

Life cycle costs consist of fuel costs, maintenance costs, human resources costs, and general-administration costs. Fuel costs were determined by thermal efficiency, fuel price, and energy produced. Fuel prices were an exogenous factor, while efficiency is within O & M contractor’s control, although equipment factors could not be separated from the analysis. This condition provided feedback loop balancing (3).
Figure 2. Causal Loop Diagram of Power Generation Business Process

Financial health was indicated by the net cash flow. Whether net cash flow was positive, the company would have more capital expenditure as well. This investment was allocated to proactive maintenance or retrofit project, which will certainly improve reliability and efficiency. Afterward, CLD in Figure 2 transferred into stock and flow diagram for model programming in Vensim (Figure 3). The model also detailed into 4 sub-structures, were: reliability/availability model, operation cost model, maintenance cost model, and cash flow model.

Figure 3. Stock and Flow Diagram
Finally, simulations were conducted with 4 scenarios: (1) O&M was undertaken by asset owner themselves, (2) O&M was outsourced to a third-party company as an asset manager, (3) O&M was outsourced within asset operator authority, or (4) partially outsourcing for certain equipment. The scenario that provided the highest NPV and availability was concluded as the best method to manage operation and maintenance.

3. Result and Discussion

Before the Vensim model simulated, several tests such as logical tests, structural tests, unit consistency tests, and sensitivity analyzes, were performed. The sensitivity test provided information to management whether some variables are sensitive to other variables. In this case, appropriate mitigation could be addressed earlier, avoiding negative impacts that might be occurred.

An offset ± 10% from basis condition was filled to the model while the other input variables remained constant. Output variables response was observed. In this study, the input variables were serious inspection (major overhaul) duration, load dispatch (expressed as a capacity factor), and coal price. The selected variable is NPV which represented cumulative profit at a certain time.

Table 1. Sensitivity Analysis Result

| No  | Parameter                        | Unit  | Input Deviation | Output Deviation |
|-----|----------------------------------|-------|-----------------|------------------|
| 1   | Serious Inspection (SE) Duration  | Day   | 20%             | 1.50%            |
| 2   | Dispatch Capacity Factor (CF)    | %     | 20%             | 53.31%           |
| 3   | Coal Prices                      | IDR   | 20%             | 62.36%           |

Table 1 shows the deviation of output variables when the input variables were varied by 20%. The table informs about the sensitivity of Serious Inspection duration, Capacity Factor, and coal price was 1.5%; 53.31%, and 62.36% respectively. Vensim also generated graphics from sensitivity analysis, shown in Figure 4.

Figure 4. Sensitivity Analysis Graph for SE Schedule Compliance (a), Coal Price (b), Power Dispatch (c)

From the table and picture above, coal price was the most sensitive to determine NPV. Increasing coal price by 10% will affect 62.36% to NPV (Figure 4b). It was a factor to be considered in the electricity business. It was different if compared to the overhaul duration effect which only swung the NPV of 1.5% (Figure 4a). Power dispatch (indicated by CF) was also quite sensitive to NPV (Figure 4c) so that O & M manager should strive to maintain thermal efficiency remains competitive in the market.
A Comparison between simulation results with reference data was performed to prove the validity of the model. Validation used the Mean Absolute Percentage Error (MAPE) method. The model was simulated by a 600 MW coal-fired plant operated by O&M outsourcing with asset manager authority.

Equivalent Availability Factor (EAF), Net Plant Heat Rate (NPHR), and coal consumption were determined as comparator variable. EAF and NPHR were chosen considering the two major KPI indicated O&M “healthiness”. Coal consumption was regarded as an independent variable because it measured from the field instrument. The MAPE validation result is shown in Table 2.

Table 2. MAPE Validation Result

| Parameter            | NPHR (kJ/kWh) | Coal Consumption (MT/month) | EAF (%) |
|----------------------|---------------|-----------------------------|---------|
| Model Result         | 2,835.36      | 211,661.25                  | 81.79   |
| Reference Data       | 2,796.88      | 206,601.58                  | 87.94   |
| Gap                  | 38.49         | 5,059.67                    | 8.34    |
| MAPE                 | 1.38%         | 2.45%                       | 5.48%   |

Because percent MAPE ≤ 10% it was concluded the model has valid and highly accurate, thus ready to be used for further simulation.

The simulation was running for 10 years (120 months) duration. The dynamics response of each scenario was observed. Availability and NPV were chosen as an objective function.

Figure 5. Dynamic Response for Availability

The graphic in Figure 5 indicates that availability fluctuates between 0 to 1. Zero availability occurred when the power plant performed overhaul. Conversely, the availability varied from 0 to 1 when the power plant was normal operation. At a glance, there were no significant differences between 4 simulated scenarios. For this reason, a chart showing the average availability over 10 years is shown in Figure 6.

Figure 6. Availability Average Comparison
Even scenario 2 provided the highest availability, 4 scenarios were slightly different. Theoretically, equipment reliability was influenced by several factors, including man, machine, method, money, tools, etc. This study focused on man and method while having no significant effect on reliability. Availability would be probably different if the machines became research variables.

Figure 7. Dynamic Response for Net Present Value

Figure 8. Net Present Value at Final Period Simulation

Dynamic response for the net present value shown in Figure 7, while NPV at 120 months shown in Figure 8. When availability was relatively constant, scenario 3 is the most profitable option. O&M outsourcing within asset operator authority was regarded as the best choice. Nevertheless, some risks related to employee competence and bureaucratic barrier should be controlled.

4. Conclusion

The work reported in this paper has managed to provide a decision aid usually faced by power plant companies, either it is as owner or it is as O&M services company. The system dynamics model of power plant business has been developed. The developed model evaluates interactions among parameter that are important in coal-fired power plant with objective of maximizing cost and maximizing profit without sacrificing power plant reliability, availability, and efficiency. Based on simulation of the developed system dynamics modeling, it can be reported that:

1. coal price was the most sensitive variable, which was equal to 62.36%.
2. From a case study conducted in a 600 MW coal-fired power plants, it was concluded that the best strategy is O&M outsourcing within asset operator authority because it provided the highest NPV.
3. The Asset owner should pay more attention to find outsourcing partners that offer competitive prices without neglecting quality because O&M service tariffs hold a fair sensitivity to NPV (4.15%)
For further study, It will be better to expand this study, not only in the operation and maintenance phase but along the whole asset life cycle from acquisition until disposal. Besides, the simulation could be addressed to other power plants with similar O&M schemes but at variance machine.

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References
[1] Kementerian ESDM 2016 Pengesahan Rencana Usaha Penyediaan Tenaga Listrik (RUPTL) Tahun 2016-2025 (Jakarta: Kementerian Energi dan Sumber Daya Mineral)
[2] Grace D 2005 Approaches to Minimizing Risk in Combustion Turbine Project : Costs for Self-Managed Maintenance Long Term Maintenance Contracts abd Insurance Update Electric Power Research Institute (EPRI) Technical update Product ID : 1004239
[3] Mercer, W B 2013 Evaluation of the Outsourcing Decisions for Power Station Operations and Maintenance Services (Canada: Athabasca University Canada)
[4] Kulkarni S A, Singh A K 2013 Outsourcing Operations, a New Trend among IPPs Infraline Plus July 2013 16-18
[5] Hartwitch F 1999 Weighing of Agricultural Research Results: Strength and Limitations of the Analytical Hierarchy Process (AHP) (Hohenheim: Institut für Agrarökonomie und Soziologie in den Tropen und Subtropen Universität Hohenheim)
[6] Sanchez J, Centeno E, Barquin J 2012 System Dynamics Modeling for Electricity Generation Expansion Analysis (Madrid: Universidad Pontificia Comillas)
[7] Kagiannas A, Askounis D, Psarras J 2004 Power Generation Planning: a Survey from Monopoly to Competition Electric Power Energy System 26 413–421
[8] Martinez I, Richardson G 2011 Best Practices in System Dynamics Modeling Proc. Int. Conf. on The System Dynamics Society (Atlanta: System Dynamics Society)
[9] Forrester J 1961 Industrial Dynamics (Massachusetts: The MIT Press)
[10] Kang K M, Jae M 2004 A Quantitative Assessment of LCOs for Operations using System Dynamics Reliability Engineering and System and Safety 87 211-222
[11] Appelin 2013 Keputusan Pengurus Asosiasi Perusahaan Penyedia Listrik Nasional No. 01/X/KEP/APPELIN/2013 tentang Alur Kegiatan Proses Pelaksanaan Pekerjaan (Jakarta: Apellin)
[12] Chung H K, Son T W 1999 System Dynamics Approach for Analyzing Dynamic Motivaton Model using Vensim Korean System Dynamics Society 61-86
[13] Coyle R 1996 System Dynamics Modelling : A Practical Approach (London: Chapman and Hall)
[14] Sontamino P 2008 Introduction to System Dynamics (SD) & Vensim Software Lecture handout (Bangkok: Mining and Material Engineering Prince of Songkla University)
[15] Sliter G 2002 Risk-Informed Asset Management (RIAM) Development Plan Electric Power Research Institute (EPRI) Technical update Product ID : 1006268
[16] The IAM 2014 The Asset Management Landscape 2nd edition www.gfmam.org
[17] Dhillon B S 2002 Engineering Maintenance a Modern Approach 10th edition (New York: CRC Press)
[18] Lewis C D 1982 International and Business Forecasting Methods (London: Butterworths)