

Reliability Issues in the Design and Operation of Process Utility Systems

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Traditional operation optimization is effective to enhance the energy efficiency of a utility system for given operating scenarios. Total operating cost will be saved, but the penalty cost caused by utility system failures cannot be considered. Optimal operating conditions from traditional optimization might have less flexibility to respond to utility system failures or maintenance and might result in a high penalty cost. In practice, it is not unusual that a unit (boiler, gas turbine, steam turbine) could fail unexpectedly, and lead to an interruption of utility supplies. If an interruption occurs, processes will need to operate at partial load or even to be shut down due to insufficient energy supply. Even though there are standby facilities that could start up in several hours, the penalty cost could still be very high during the response time of utility systems. Safety implications might demand that the system be designed to operate under all possible circumstances. A balance between operating cost and penalty should be achieved for the minimum overall total cost. To obtain the true cost, an analysis of system reliability, availability and maintainability (RAM) is essential. Moreover, not only the operating conditions should be optimized, but also operating strategies should be selected properly, e.g. cold standby, hot standby, load-sharing, etc. A novel optimization methodology has been developed to systematically minimise overall cost by considering utility system failures, maintenance requirements and different operating strategies. Maximum overall site profit will be obtained through advanced optimization with RAM analysis.

1. Background

Most of the process industries rely on utility systems to provide the energy, e.g. steam, cooling water, fuel, which are transformed from the primary inputs, such as water and fuel. As shown in Figure 1, a typical utility system usually contains a series of units with complicated interconnections, including boilers, steam turbines, gas turbines, etc. In order to fulfill various energy demands under different circumstances (e.g. energy prices, ambient temperatures), utility systems must be designed and operated in a flexible way. Besides, it is not unusual that equipment items could fail unexpectedly, and then affect the production of downstream processes with various penalties. It is essential to design and operate utility systems in a reliable way in order to appropriately

respond to the unexpected failures. Hence, potentials exist to achieve considerable savings in operating cost, downtime penalties and capital investment.

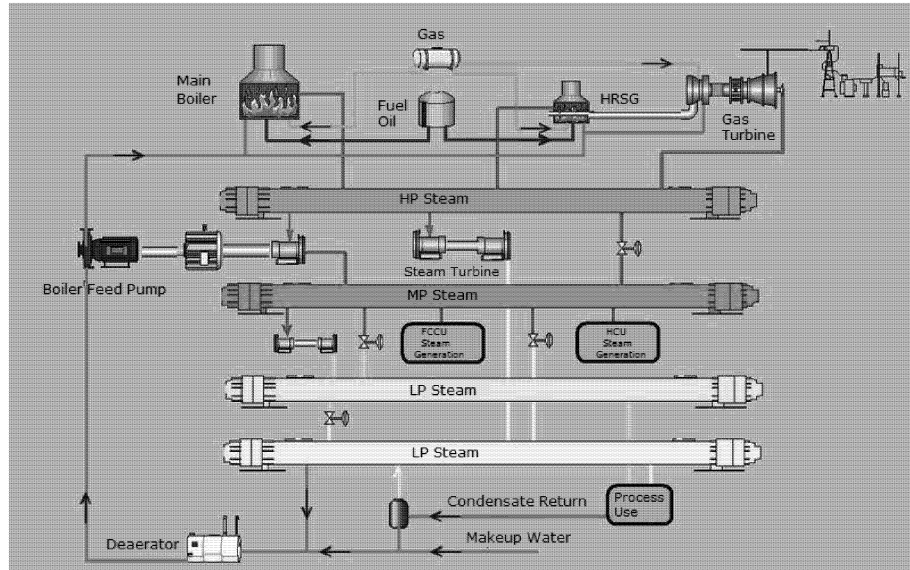


Figure 1: A typical utility system flowsheet

Considering the uncertainties during the operation of utility systems, for instance, changes in the steam demand at short notice, various electricity tariffs with time, scheduled equipment maintenance, and especially, unexpected units failures, utility systems are usually designed with excess capacity. There are different operating strategies to manage the redundant capacity. E.g. cold standby strategy – redundant boilers are in off mode and will only be started up when necessary; load-sharing strategy – all boilers are operating together to share the load; hot standby strategy – redundant boilers are heated intermittently to be maintained at the saturation temperature but without steam output. When necessary the load can be increased in a short period of time. Since different operating strategies perform differently when responding to the uncertainties, especially unexpected equipment failures, the strategy should also be optimized in addition to the conventional optimization on the selection of fuels, the steam paths between steam headers, the working conditions and loads of each unit, etc. However, the reliability issues and flexibilities in the operating strategies are usually ignored in the traditional optimization approach.

The conventional optimization approach focuses on optimizing the operation conditions in a steady state, normally the initial state without any equipment failures. The objective is to minimize the operating cost or maximize profit. In this case, it is essential for the units to be operated at higher efficiency to reduce the fuel consumption. Hence, boilers are pushed to be operated at higher capacity to obtain better heat efficiency. Redundant boilers are left in cold standby mode. But this steady state would easily be disturbed especially due to equipment failures. Suppose an operating boiler fails unexpectedly, the standby boiler should be switched on immediately. However, it takes hours to complete

the start up process. During this period, it is quite possible that energy demand can not be satisfied. The downstream processes have to reduce their production or even to be shut down, which causes economic penalties. Therefore, the ignorance of equipment failures in the conventional approach will lead to non-optimal operating strategies to manage the redundancy. Some other studies consider the reliability in a simple way by predetermining the probabilities of some worst scenarios with a fixed figure (Aguilar, 2005). But this is not enough or accurate. Alternatively, in the industrial practice a conservative operating strategy – load-sharing is more often employed. Since for an operating boiler the load can be increased in several minutes, the system is able to respond immediately to the unit failures. In this way, lost production penalties will be reduced. But lower capacity means lower heat efficiency. As a result fuel consumption will be increased as the compensation. Seldom can be seen a systematic way of optimizing operating conditions together with strategies and reliability considerations. Moreover, reliability issues should also be considered in the design stage of utility systems. Different redundancy configuration can be implemented. For instance, two larger units or 3 smaller units are both applicable to satisfy the system demand. The first option has lower purchase and construction cost, but it makes the utility system under more risks suppose one of the two boilers fails unexpectedly. The second option can reduce such risks, but the on the other hand purchase and construction cost would be higher as the cost. A traditional way to integrate the redundancy optimization is to predetermine a certain level of capacity redundancy by rules of thumb, e.g. 20% - 30% extra capacity, or an N+2 philosophy. The former one is to design the system configuration according to the total capacity with extra redundancy. The latter one is to employ another two units as the standby. Both of them are not sophisticated. The paper proposed a systematic approach to integrate reliability considerations into the optimization of design and operation of utility systems, with balanced operating cost, penalties and capex. The optimization framework not only involves the working conditions of each unit, but also exploits the appropriate operating strategies.

2. Operation Strategy Optimization

The proposed approach considers the probability and effects of equipment failures in a systematic way when optimizing the utility system operation strategy. A states-based theory is used to calculate system reliability performance. Due to the uncertainties a system cannot always stay in the same initial state. Equipment failures and repairs will make the system jump from one state to another. For example, suppose in the initial state Boiler A is in operation mode, and Boiler B is in cold standby mode. If Boiler A fails unexpectedly, then the system will fall into another new state that Boiler A is under repair while Boiler B is being started up. The system could have various states with different probabilities of each state, as well as different economic performance. Some states could have better profit, while some others could generate penalties due to equipment failures. In the proposed methodology the performance of each state is weighted according to the probability of its occurrence. In this way the system overall performance can be obtained with the considerations of penalties due to equipment reliability issues.

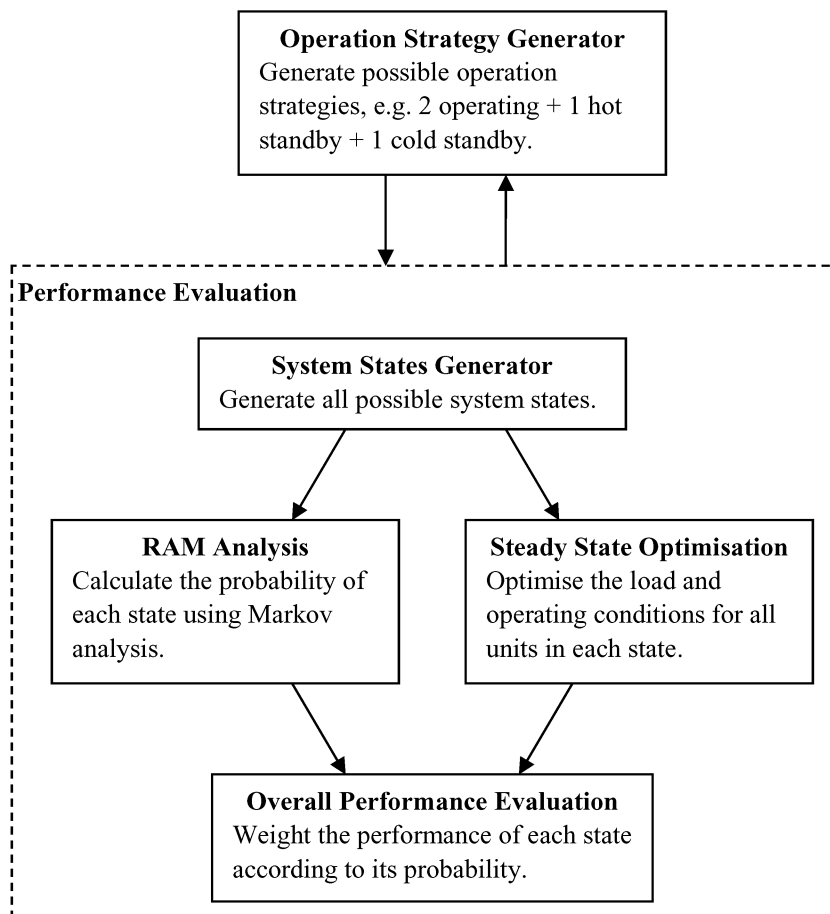


Figure 2: Optimization framework of the operating strategy

The framework of the optimization approach is shown in Figure 2. Given a fixed utility system configuration and energy requirements, a certain operation strategy will be generated, e.g. Boiler A and B are in operation mode; Boiler C is in hot standby mode; Boiler D is in cold standby mode. Then an evaluator will conduct the analysis to obtain the system overall performance. As the basis of the evaluation, all possible system states will be generated according to the system configuration and the operating strategy. On one hand system reliability and availability are analyzed using Markov method (Henley, 1989). The probability of each state is calculated based on the transfer rate between states. The transfer rates actually depend on the equipment characteristics on the failure, repair, start-up, etc. On the other hand a steady state optimization is conducted for each state to obtain the working conditions of each unit in that particular state with the target of minimizing operating cost or maximizing profit (Oscar, 2005). Finally, the overall

performance is evaluated according to the economic performance and the probability of each state.

The operation strategy generator continues to generate possible strategies and conduct the system performance evaluation to each strategy. In the end, the best strategy can be found by comparing their objective functions.

The proposed approach not only optimizes the best working conditions for each item in all possible scenarios, but also the redundancy management strategy with the consideration of reliability issues.

3. Design Optimization

Reliability issues should be considered in a sophisticated way in the optimization of the utility system design. The proposed approach employs a systematic methodology to design the redundancy configuration. In addition to the consideration of operating cost, the capital investment is involved as well. More spare units means a better reliability and availability which leads to less downtime penalties. But it also means more capital investment for the construction. The trade-off among penalties, operating cost and capex can be found by the proposed approach.

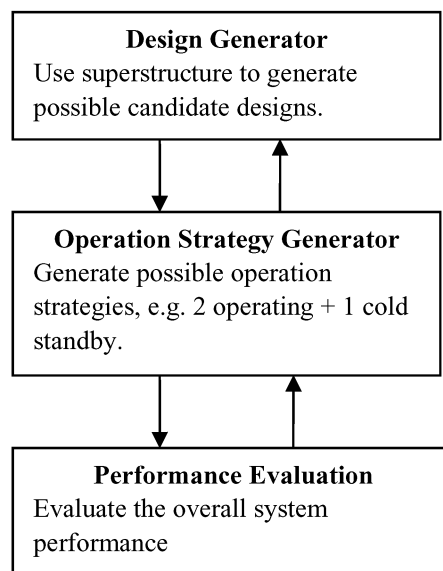


Figure 3: Optimization framework of the utility system design

Figure 3 shows the optimization framework in the utility system design. Superstructure is used to generate possible candidate designs. For a particular design, the operation strategy will be optimized according to its overall performance, which is evaluated based on performance of each system state and its probability. Then different designs are compared according to their best performances. Hence, the best design is now obtained.

The proposed approach integrates the optimization of the design, operating conditions of each unit and operation strategies into the same framework. By introducing the state-based analysis in to the framework, all possible states with equipment failures, repairs, start-ups, etc. are evaluated. Therefore, penalties due to the equipment failures are able to be calculated in a systematic way. In the process of seeking the optimum design configuration, the operating cost, penalty cost and capital invested are balanced together. With the considerations of equipment reliability, non-optimal design (with lower capex and operating cost, but higher penalties) can be avoided.

4. Summary

While the traditional approaches to optimize the operation of utility systems either neglect the probability of equipment failures or use a predetermined figure to define the probability of unit failures, the proposed approach is able to evaluate the effect of the reliability issues in a systematic way. According to the methodology, not only can the operating strategies be optimized in each particular system state, but also the optimum operating strategy, e.g. cold standby, hot standby and load-sharing strategy. The best strategy can assure the lowest total cost which comprises operating cost, downtime penalties, etc. Moreover, this optimization approach has been integrated into the design of utility systems. Penalties due to equipment failures are balanced with the capital investment and other operating cost. Only in this way can never an optimum design be missed. This approach has been successfully applied to the practical cases.

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