

Optimising the design and operation of industrial utility plants subject to variable demands and prices

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Abstract

Most industrial sites satisfy their heat and power needs through utility plants, which convert basic energy/water feeds into steam, electricity and rotational power. These systems offer the opportunity for substantial savings given their large investment requirements and operating costs. However, minimising such expenditure also represents a very challenging task due to the large number of design choices and complex operating interactions among their units. This work proposes a novel methodology for the design and operation of utility plants, which fully exploits their inherent flexibility when they are subject to variable conditions (e.g. demands, prices, ambient temperature). The suggested MILP formulation allows structural and operational parameters to be optimised simultaneously and the procedure is robust enough to tackle real industry problems.

Keywords: Utility systems, synthesis, operation, cogeneration, flexibility.

1. Introduction

Every industrial activity requires utilities to operate and, in the case of complex transformation processes with several plants consuming large amounts of energy and water, it is more economic to build an in-site utility system to satisfy these demands. Therefore, the design and operation of utility systems offer the potential to achieve considerable savings, but also represent very challenging tasks.

On one side, pure operational problems apply to existing utility plants in which structural changes are not contemplated. In such cases the objective is to establish the conditions (e.g. temperature, pressure, mass flow) for all streams of the plant flowsheet that will minimise operating costs given certain energy/water demands. Even with a fixed configuration there is normally a great number of alternatives to satisfy these requirements and all of them should be evaluated simultaneously. Due to its complexity, in the past several authors have employed mathematical optimisation techniques to address the operational problem (e.g. Iyer and Grossmann, 1997; Shang and Kokossis, 2000; Varbanov et. al. 2004).

On the other hand, for pure grassroots design problems it is necessary to define the types of units to be employed, their number, sizes, and interconnections among them assuming constant demands and all units operating at full load. Again there have been

many research works dealing with these tasks through the use of mathematical programming tools (e.g. Papoulias and Grossmann, 1983 and Bruno et. al. 1998). However, these conventional approaches for the design of utility systems cannot take into account several operating scenarios simultaneously or consider part-load operation of the equipment.

In response to these limitations, there have been approaches combining elements of both operational and design problems. Hui and Natori (1996) evaluated several retrofit options along different operating conditions through a MILP model. Maia and Qassim (1997) employed simulated annealing to select the optimal configuration for a utility system subject to variable demands. Maréchal and Kalitventzeff (2003) applied a multiperiod MILP formulation to choose the optimal utility plant design from several choices obtained from targeting techniques.

In all these cases equipment sizes and loads are not optimised simultaneously as continuous functions and, moreover, the user must pre-specify certain design options with fixed-sized units that often miss better alternatives. Therefore, the present work proposes a common optimisation framework for the design, retrofit and operation of utility plants under variable operating conditions. The suggested method fully exploits the flexibility of these systems by considering part-load operation for all units within a simultaneous structural and operational optimisation.

2. Equipment Modelling

Mathematical models are employed to predict the performance of each piece of equipment within the plant and simulate/optimize the whole system. Although there are many types of models and optimisation techniques currently available, linear modelling offers robust and reliable routines suitable for real industry problems. Conventional linear models determine the equipment performance either as a function of load (i.e. fixed unit sizes) or as a function of size assuming full-load operation. While such approaches are suitable for pure operational or design problems, in order to carry out simultaneous structural and operational optimisation it was necessary to develop novel generic models predicting equipment performance as a linear function of both unit size and load.

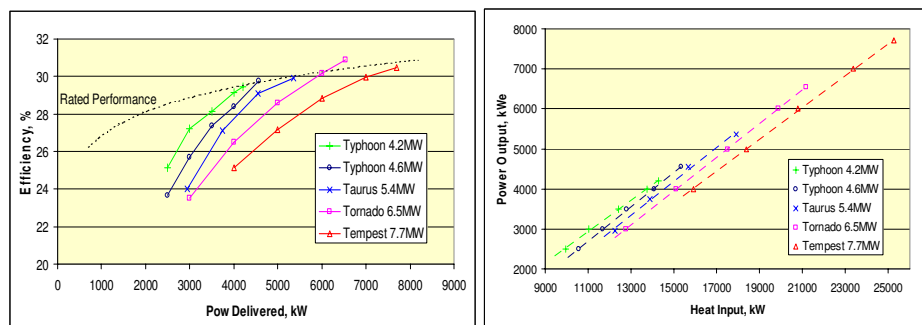


Figure 1. Efficiency non-linear curves appear as linear trends when plot axis are changed

The proposed models can reflect non-linear efficiency trends employing linear equations but without resulting in excessive computational expenditure (i.e. without

piece-wise linearisation). The key feature to achieve this is to avoid the explicit calculation of the efficiencies during the optimisation as they can always be obtained afterwards (e.g. dividing power produced over fuel consumed). Figure 1 illustrates the fact that non-linear efficiency curves correspond to linear trends when the information from the first one is presented on an output vs. input plot. In other words, both graphs are perfectly equivalent and plots of the second type have been used to derive the present models directly from manufactures data with good accuracy for preliminary design purposes (i.e. errors $\pm 5\%$). During the present work, novel models have been developed for boilers, steam turbines, gas turbines, heat recovery steam generators (HRSG), and electric motors. Even though a detailed description of them goes beyond the scope of this paper, they all adhere to the following structure:

$$Output = A \times Design_Input + B \times Actual_Input + C \quad (1)$$

Where A, B, C are regression parameters

3. Proposed Methodology

In order to handle varying conditions, a multiperiod optimisation has been implemented in which different scenarios can be defined. Thus, the resulting data defines not only a plant configuration that can cope with all the specified fluctuations, but also it establishes how to operate the system during each scenario. In this sense, the proposed approach adds a new dimension to the conventional (pure) design problem since the optimum solution will now depend on both structural and operating parameters.

As expected the optimisation task becomes more complex but by employing the suggested models it is possible to generate a mixed-integer linear (MILP) formulation for which the objective function to minimise is total cost:

$$TotalCost = \sum_n CapitalCost_n + \sum_p OperationCost_p \quad (2)$$

$$OperationCost_p = [Fuel + Water + Electricity + Emissions]_p \quad (3)$$

$$CapitalCost_n = F_{ann} [F_{inst} * PurchaseCost]_n \quad (4)$$

Where:

n is the index for selected equipment units F_{ann} is the annualisation factor

p is the index for operating scenarios or periods F_{inst} is the installation factor

The major constraints for the objective function are energy and mass balances together with equipment performance equations. While the capital cost of each unit is a function of the selected sizes, operational costs will depend on equipment sizes and their actual loads. Performance of all units will translate into different quantities of overall fuel and water requirements, electricity import/export, and emissions for every operating scenario. Note that the emissions are obtained from stoichiometric relations upon the fuels being consumed.

Whilst the mathematical formulation employs continuous variables to define, for example, equipment sizes and loads, binary variables are used to select the units of the

plant and designate whether they operate or not during a certain scenario. Structural decisions are taken from a super-configuration that can include user specifications (i.e. flexible superstructure) to tackle retrofit or pure operational problems by fixing some or all the structural elements of the system.

3.1 Mechanical Driver Selection

Shaft power for rotational equipment (e.g. fans, compressors) can be provided in many different ways. However, conventional approaches for the synthesis of utility systems only consider pre-specified types for driving units with fixed size. Therefore, another innovative feature implemented in this work is an exhaustive driver selection to satisfy mechanical power demands.

Large driving units have complex interactions with other equipment in the utility plant and can considerably affect the final design and operation of the whole system. Furthermore, it is possible to achieve significant savings if drivers are selected in an integrated context during the synthesis procedure.

Figures 2a and 2b illustrate how a large number of driver options can be included in the superstructure for configuration decisions. Shaft demands can be satisfied with gas turbines with or without HRSG, back-pressure or condensing turbines through different expansion paths, electric motors or a combination of all of them. Moreover, the number and sizes of the units attached to a single shaft are also unknown. In this manner, the types, number, sizes and loads for all drivers are optimised together with the rest of the utility system.

3.2 Equipment Redundancy

The design of a utility system should also make allowances for equipment being unavailable due to maintenance and unexpected failure. As a result, plants operate with some redundant equipment (i.e. spare or oversized units) most of the time. In conventional design routines a discretionary number of additional units or fixed oversizing factors are assumed to cope with these concerns. Nevertheless, given the possibility of simultaneous structural and operational optimisation, the proposed methodology can establish an optimal equipment redundancy and attain large savings in capital expenditure. For instance, users can define several scenarios and specify failure conditions in some of them, so that the final design will cope with all situations at a minimum cost.

For example, if the operating horizon of a plant is divided into maintenance time intervals and each unit is forced to be shutdown at least during one of these periods, then the optimiser will establish at the same time the operational planning (scheduling) and the redundancy due to maintenance that will minimise total cost. In addition, since two units failing independently at the same time is very unlikely, optimal redundancy due to unexpected failures can be also obtained by forcing in certain periods the shutdown of the two largest units of each type (i.e. one of them fails while the other one is receiving maintenance). Hence optimisation might cope with such situations by adding new equipment, increasing the size of some units or by importing/exporting more/less utilities (e.g. electricity). It is worth mentioning that the size or the types of units that will be employed as redundant equipment is not known before hand so the procedure will determine the optimal equipment redundancy without the use of any heuristic or rule of thumb.

4. Study Case

The capabilities of the proposed methodology are briefly demonstrated with a retrofit case. An existing utility system must satisfy a new set of demands due to the incorporation of another process plant. Demands and site data are provided in table 1 for two seasons with different electric tariffs in each one.

Table 1. Site and demands data for the study case. Note how different electric tariffs apply to each season.

PARAMETER	UNITS	VALUE		NEW DEMANDS	
		Base	Summer	Base	Summer
Fraction of the year	%	67.0	33.0		
Ambient temperature	°C	10.0	25.0		
Electric prices: Peak	\$/kWh	0.07	0.08		
	Off-peak	0.05	0.05		
Peak hours per day	hrs	7.0	12.0		
Fuel oil cost	\$/kg	0.19	0.19		
Natural gas cost	\$/kg	0.22	0.22		
Raw water cost	\$/ton	0.05	0.05		
Electricity demands	MW	62.0	68.0	81.0	89.0
Steam demands	MW	424	382	593	534
Condensate return	%	80.0	80.0	80.0	80.0
Power pump 1	MW	5.2	5.0	7.2	7.0
Power pump 2	MW	1.3	1.1	1.8	1.5
Power pump 3	MW	2.2	2.0	2.8	3.0
Power pump 4	MW	0.6	0.6	0.8	0.8
Process CW demands	MW	200	300	280	420

A conventional method to deal with the problem is to test many reasonable retrofit options with an operational optimiser and select the one yielding best results. However, this approach can hardly evaluate all possible alternatives. A promising answer obtained in this way is presented in Figure 2a. New equipment is highlighted, two more boilers of the same size plus a back-up are provided and additional steam is expanded through new turbines for generating electricity or delivering mechanical power. Required investment is 62.0 MM\$ and the operation cost is 111.0 MM\$/yr.

A different retrofit design results when the suggested methodology is applied as seen in Figure 2b. There are still three additional boilers but the third one is of a smaller size. Cogeneration potential from extra steam available is also exploited in turbines, but through different expansion paths. Required investment is only 39.0 MM\$ with an operational cost of 108.8 MM\$/yr (savings of 23.0 MM\$ and 2.2 MM\$/yr respectively). Note that other design options can be explored depending on the amount of capital available.

5. Conclusions

A novel methodology to optimise the design and operation of flexible utility systems has been developed. The proposed modelling framework allows simultaneous structural and operational optimisation to tackle grassroots, retrofit and pure operating problems. The multiperiod MILP formulation can handle varying conditions in which equipment

sizes and loads become variables. It is also possible to establish at the same time optimal redundancy, maintenance planning for all units, and carry out an exhaustive driver selection in order to minimise costs. The approach is robust enough to tackle real industry problems.

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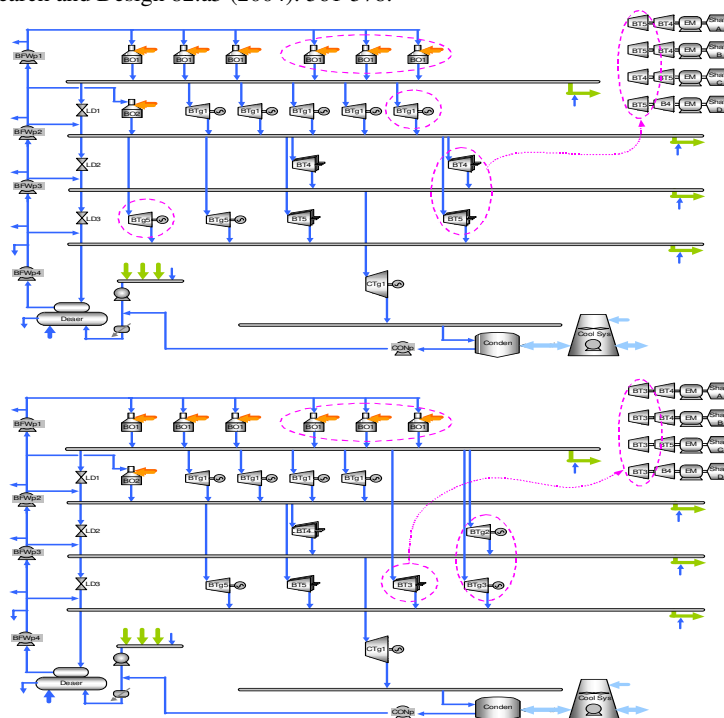


Figure 2. a) Promising retrofit solution for the study case obtained with conventional methods.
b) Optimal answer resulting from the proposed methodology