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Resilient Decision Making in Steam Network Investments

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Steam is a key energy vector for industrial sites, used for process heating, direct injection and stripping, tracing and cogeneration of mechanical power. Steam networks transport steam from producers to consumers and across different pressure levels. The steam production equipments (boilers, cogeneration units and heat exchangers) should be dimensioned to always supply key consumers as well as to deal with extreme demand caused by exceptional events such as unit startups or extreme weather. An important issue to be dealt with is that of unexpected boiler shutdowns, which can take significant amounts of time to bring back online. In cases where demand surpasses the available production of steam, load shedding is necessary in order to keep the network operable. A penalty cost can be associated to load shedding. A well dimensioned steam network is one which is resilient to such events, being able to overcome extreme demand and unexpected boiler shutdowns at minimum cost.

This paper proposes a methodology for evaluating the operability of a steam network when facing unexpected boiler shutdowns. A Monte-Carlo simulation is carried out on a multi-period steam network problem, randomly shutting down boilers according to their failure properties (probability of failure and duration of failure). The aim of this method is to evaluate how resilient a steam network is to boiler shut-downs.

The Monte-Carlo simulation is applied to a steam network model built using a Mixed Integer Linear Programming (MILP) formulation, whose objective function is to minimise the operational costs of the steam network and therefore also to minimise the penalty costs associated to load shedding. A case study based on anonymised industrial data is used to demonstrate the method. Two investment propositions are evaluated and compared using the proposed method.

1. Introduction

Steam networks deliver energy to processes, in the form of mechanical, thermal and chemical energy. As such they are a key energy driver for industrial sites. The steam producing equipments within a steam network, typically boilers or cogeneration units, must have a high enough capacity to supply steam to the process units at all times, despite exceptionally high demand (for example caused by unit startups), foreseeable events (boiler turn-abounds) and unforeseeable events (boiler failures). Redundancy is usually built into steam networks through the oversizing of the boilers and through the construction of back up units, implying important investment costs. Boiler failures are not everyday events in industrial sites, but happen often enough to require contingency plans (Pfeuffer, 2009).

In this paper we propose a methodology for evaluating the resilience of investment propositions in steam network. The size and number of back up equipments in order to ensure a resilient steam network. A Monte-Carlo sampling algorithm is applied to a steam network optimization problem, formulated using Mixed Integer Linear Programming (MILP), to randomly shut-off steam producing equipments according to their failure rates and durations. By repeating this step many times and studying performance indicators, an image is obtained of the resilience of the network, that is to say its ability to overcome boiler crash events. A further analysis would also highlight configurations of demand which lead to the highest risk.

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Steam network modelling using MILP formulations (Papoulias and Grossmann, 1983) permitted the use of mathematical tools to optimally distribute steam between producers and consumers. The extension to multi-period (Iyer and Grossman, 1997) created the perspective for operations optimisation. Mixed Integer Non Linear Problem formulations (Varbanov et al., 2004) bring more exact solutions as well as the possibility for detailed energy balances at the cost of more computing power. Further extension of the MILP formulation to introduce load shedding (Bungener et al., 2015) in order to overcome situations where steam demand surpasses the capacity of the steam producing equipments allows for the realistic evaluation of steam networks facing common challenges. These papers leave two questions open; how to size a steam network and how to deal with boiler failures which are an everyday reality of steam network operations.

A methodology describes a steam network model with load shedding, followed by a Monte-Carlo sampling algorithm to simulate boiler failures. This simulation allows the evaluation of a steam network under different operating conditions, to determine its resilience. To demonstrate the methodology, a case study based on data from the steam networks of two adjoining industrial sites compares two investment options, one with low redundancy and low investment cost and one with more redundancy and higher investment cost.

2. Methodology

The methodology is broken down into two parts. Firstly a steam network model is described and secondly the developed Monte-Carlo sampling methodology is explained.

2.1 Steam network

An MILP formulation was previously developed (Bungener et al., 2015) to optimise the operational and investment costs of a steam network while ensuring the transfer of steam to and from units. Units can be boilers, process units, turbines or letdowns. Process units can also produce steam. Each unit is associated to a flow of steam (with *N* the set of flows) to a header (*H* the set of headers) and to a steam network *S* (several independent steam networks can exist in the same model). A binary variable y_{nt} is set for each of the *n* units and the *t* times, describing whether or not the unit is used. A binary parameter Y_{nt} defines whether or not a unit can be shut off. A continuous variable F_{nt} describes the utilisation rate of unit n at time t. Lower bounds ($F_{\min,nt}$) and upper bounds ($F_{\max,nt}$) are set for each unit and for each time. Several constraints are described below, thereby creating the steam network model.

Eq(1) forces the use of certain units, for example process units.

$$y_{nt} \geq Y_{nt} \quad t = 1..T, \; n = 1..N \tag{1}$$

Eq(2) ensures that utility equipments such as boilers, letdowns and turbines are kept within their lower and upper bounds.

$$F_{\min,nt} y_{nt} \leq F_{nt} \leq F_{\max,nt} y_{nt}, \; Y_{nt} = 0 \quad t = 1..T, \; n = 1..N \tag{2}$$

Eq(3) sets the unit flowrate for non shedable process units while Eq(4) does the same for shedable units.

$$F_{\min,nt} = F_{\max,nt}, \quad {}_{nt} = 1 \quad \forall n,t \tag{3}$$

$$F_{\min,nt} = F_{\max,nt}, \; y_{nt} = 0 \quad \forall n,t \tag{4}$$

Eq(5) sets the mass balance for each header and for each time.

$$\sum_{n \in I_h} F_{nt} - \sum_{n \in O_h} F_{nt} = 0, \qquad \forall n,t, \; h = 1..H \tag{5}$$

The order of priority in which units can be shed is defined for each steam network, with G_{ps} the set of flows of priority p in steam network S, and is constrained using Eq(6).

$$y_{nt} / n \in G_{p,s} \geq y_{nt} / n \in G_{p-1,s} \geq ... \geq y_{nt} / n \in G_{1,s} \quad \forall n,t, \; s = 1..S \tag{6}$$

Steam letdowns transport steam from a steam header to a lower pressure steam header to which a fixed desuperheating factor w_t can be associated as described in Eq(7). Turbines are defined as letdowns which simultaneously produce mechanical power, using constant conversion efficiency.

$$\sum_{n\in O_l} F_{nt} - \sum_{n\in i_l} F_{nt}(1+w_l) = 0, \qquad \forall n,t,\ l = 1..L \tag{7}$$

The objective function of the MILP formulation, Eq(8), is to minimise the operating costs of the steam network, with c_{nt} the cost of operating unit n at time t, P_n the shedding penalty associated to unit n, e_t the price of electricity at time t, W_{nt} the electricity produced by flows n at time t.

$$OPEX_{nt} = c_{nt}F_{nt} + (1-y_{nt})P_n - e_t W_{nt} \quad \forall n,t \tag{8}$$

2.2 Monte-Carlo sampling methodology

The proposed methodology uses Monte-Carlo sampling to randomly shut down boilers according to their failure rates. The duration of the shutdown is also a randomly generated variable, which depends on the boiler properties. Each of the B boilers are associated to a failure rate f_n and a maximum failure duration d_n. The failure rate is the probability that a boiler will fail over a period of time T. The maximum failure duration represents the maximum amount of time that a boiler will be offline following a fail, which must be a multiple of the time step of the problem.

For each time step and for each boiler, a random variable x_{nt} is generated from a uniform distribution between 0 and 1. A second random variable d_{nt} is generated between 1 and d_n. If x_{nt} is smaller than or equal the failure rate, the boiler in question is forced to be off for duration y_{nt}.

$$\forall t \in [1,\ldots,T], \forall n \in [1,\ldots,B] \begin{cases} x_{nt} \le f_n & F_{\max,ns} = F_{\min,ns} = 0 \quad s \in [t,\ldots,t+d_{nt}] \\ x_{nt} > f_n & F_{\max,nt} = F_{\max,n} \quad F_{\min,nt} = F_{\min,n} \end{cases} \tag{1}$$

The algorithm proceeds as follows. Firstly data is initialised. The boilers are sampled using the above described methodology. The steam network optimisation can then take place. The objective function of optimisation is recorded. The iterative process can start again, with the re-initialisation of the data. This loop is repeated n times. The average objective function over all the iterations allows judging the simulated cost of the system over time T.

3. Case Study

A case study is proposed to demonstrate the method. Two steam networks belonging to adjoining industrial sites are considered, using a year of industrial data. The steam networks are firstly described, followed by a case study using the developed methods.

3.1 Description of steam networks

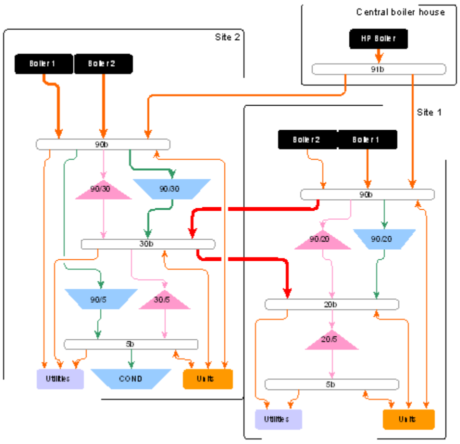

Figure 1 Illustration of adjoining steam networks

The case study in this paper considers the two steam networks, associated to two independent industrial sites. Both sites contain their own boiler houses, which produce steam at high pressure. The steam networks are illustrated in Figure 1.

Process units consume steam at a total of 4 different pressure levels. A central boiler house supplies steam to both sites when demand surpasses organic production abilities, with a maximum capacity of 200 t/h. produced at 30 bars. The central boiler house is operated as a joint venture between both industrial sites. Tables 1 and 2 describe the key properties of the boiler equipment of both sites the sites. Both sites can activate letdowns when steam demand is high in order to produce additional steam through desuperheating.

Table 1: Properties of steam network 1's key equipments.

	Inlet [bar]	Outlet [bar]	$F_{\min,n}$ [t/h]	$F_{\min,n}$ [t/h]	Failure rate [-]	Max fail duration [d]	Other
Boiler 1&2	-	90	30	90	0.0027	15	19 €/t
Turbine 1&2	90	20	52	90			$\eta_{isentropic}$ = 0.7
Letdown 1	90	20	0	200			w_l = 0.12
Letdown 2	20	5	0	200			w_l = 0.6

Table 2: Properties of steam network 2's key equipments.

	Inlet [bar]	Outlet [bar]	$F_{\min,n}$ [t/h]	$F_{\min,n}$ [t/h]	Failure rate [-]	Max fail duration [d]	Other
Boiler 1&2	-	90	50	160	0.0027	12	20€/t
Turbine 1	90	30	50	112			$\eta_{isentropic}$ = 0.7
Turbine 2	90	20	13	60			$\eta_{isentropic}$ = 0.7
Turbine C	5	1	13	30			$\eta_{isentropic}$ = 0.6
Letdown 1	90	30	0	200			w_l = 0.08
Letdown 2	30	5	0	200			w_l = 0.10

The industrial sites operate their steam networks independently, though they can send steam to each other through relief lines (in red in Figure 1). Site 2 is able to relieve Site 1 with high pressure steam (90 bar) which is letdown to 30 bar, while Site 1 is able to relieve Site 2 with 30 bar letdown to 20bar. Figure 2 shows the demand of steam for both sites for a time scale of 365 d. Site 1 supplies and receives steam from 6 process unit complexes at each pressure level. Its mean steam demand is 163 t/h with a peak of 207 t/h. Site 2 also supplies steam to 6 process unit complexes though 30 bar and 5 bar steam is produced by its units. Its mean demand is 339 t/h with a peak value of 475 t/h. Shedding priorities for both sites are set according to unit importance. Penalty costs associated to shedding rise with the priority level of a unit. Figure 3 shows the combined load duration curves for both sites. For more details about the case study, please refer to Bungener et al,. 2015.

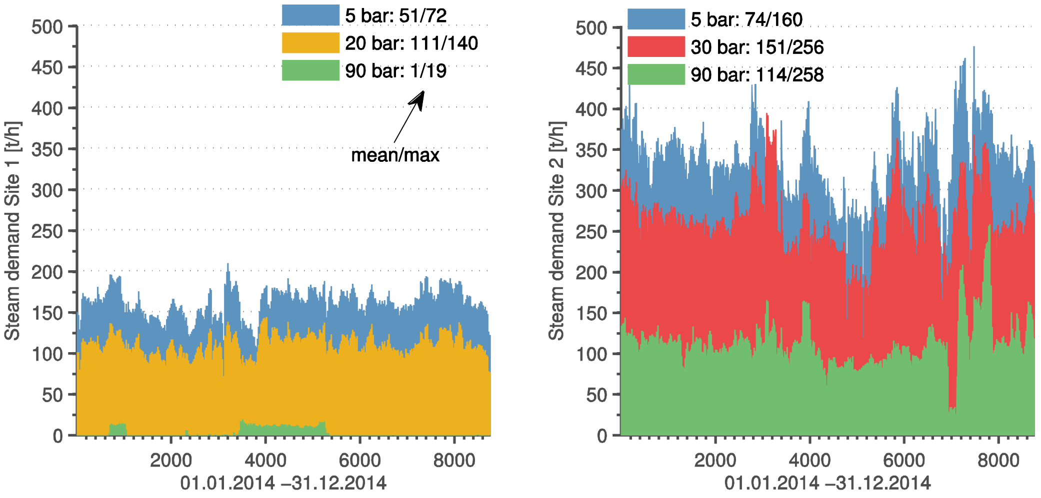

Figure 2 Steam demand for both industrial sites

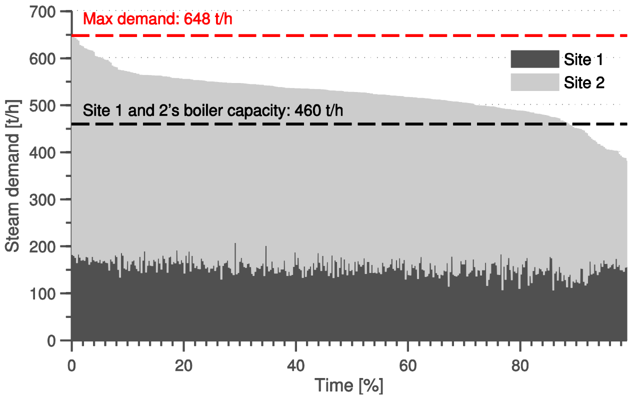

Figure 3 Demand load duration curves of combined sites

In this case study, we consider that the central boiler house is to undergo total refurbishment as the boilers no longer meet emissions standards. Two investment options into medium pressure boilers to supply both sites are proposed as described in Table 3. Scenario 1 proposes to invest in a single boiler with a 200 t/h capacity costing 30 M€ while scenario 2 proposes to invest in two smaller 100 t/h boilers, at a higher combined cost of 34 M€. Annualised costs are considered for the boilers with an interest rate of 6 % over a duration of 25 y. All of the boilers (including those in Site 1 and Site 2) are submitted to the Monte-Carlo sampling.

Table 3: Investment choices for central boiler house

	Pressure [bar]	$F_{\min,n}$ [t/h]	$F_{\min,n}$ [t/h]	Failure rate [-]	Max fail duration [d]	Cost [€/t]	CAPEX [M€/yr]
Scenario 1	30	60	200	0.0027	15	19.8	1.5
Scenario 2	30	2x40	2x100	0.0027	12	20.0	1.7

3.2 Results of operating cost simulation

The simulation goes through 500 iterations for each scenario. The total costs are calculated in M€/yr and correspond to the sum of the investment costs (CAPEX) and simulated operational costs (OPEX). The design total costs are the sum of the CAPEX and design OPEX. The scenarios are also run without any boiler failures in order to determine operational costs under design conditions. The economic results from both scenarios are shown in Figure 4. Design costs are shown in green, while the results of the simulation are shown in black, with the average value in blue. The red curve at the bottom of the figures shows the standard deviation of the simulated costs to determine its convergence.

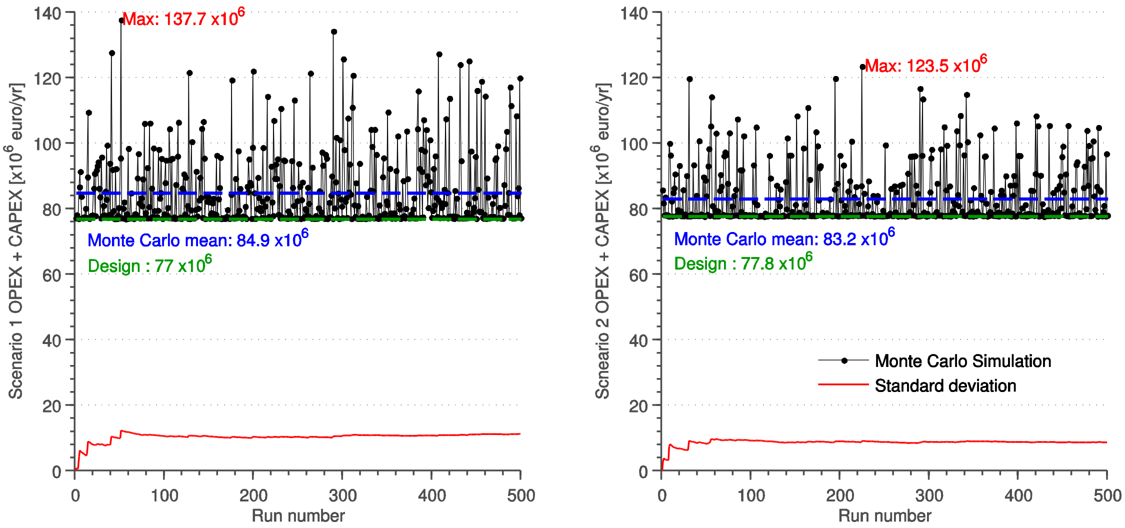

Figure 4: Economic results of simulation

Results indicate that design costs are slightly higher for the second scenario, a logical result of its higher operational costs (see Table 3). However if boiler failures are taken into consideration the second scenario is 1.7 M€ less expensive, as indicated by the Monte-Carlo mean. In scenario 1, as there is only one boiler, if a boiler failure occurs, 200 t/h of steam production capacity is removed from the system. In scenario 2, a boiler failure removes only 100 t/h of steam production capacity. Given the low failure rate of the boilers, it is highly unlikely that both boilers will go offline at the same time, therefore boiler failures will generally remove 100 t/h of steam production capacity. For the same reasons, the maximum costs of the simulations are higher in scenario 1.

4. Conclusion

A methodology has been proposed for evaluating the resilience of investment propositions in a steam network. A steam network optimization model was developed using a MILP formulation, including the possibility of load shedding when demand surpasses the possible supply of steam. In order to evaluate the costs of the steam network while taking into consideration unexpected boiler failures, a Monte-Carlo sampling algorithm was used to randomly shutoff boilers according to their failure rates and durations. This sampling is repeated many times in order to simulate the operations of the steam network over a year of operations.

A case study based on industrial data was used to demonstrate the method. Two investment options were investigated in order to replace an ageing boiler house, with a choice of one large boiler, or two smaller boilers. Results indicated that by investing in two boilers rather than one, the simulated yearly costs of the steam network could be reduced, as penalty costs associated with undercapcity were reduced.

It should be noted that with a different pricing strategy, for example using payback times, the scenario with a single boiler would have been more economically interesting.

While the analysis of this case study was fairly brief, many more performance indicators could have been evaluated to properly understand the behaviour of the network. Studying the frequency of load shedding and the configurations which lead to the highest penalty costs would also have been very revealing.

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