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Implementing the simulated annealing algorithm to optimize the startup of a drum boiler

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Abstract

Thermal power plants are a reliable source of electricity. To improve their competitiveness in the electricity markets, they must improve their operational procedures to be more efficient. Being one of the most important components of a thermal power plant, the drum boiler has the potential to improve the competitiveness of a thermal power plant by means of the reduction of its startup time. However, if startup is carried out too fast, excessive thermal stresses can occur in the drum boiler components. In this paper, we propose a dynamic optimization approach that takes into account the mechanical integrity of the equipment. The optimization is carried out by means of the simulated annealing algorithm with a solution representation of 3 chromosomes to synthesize the optimal operational procedures for the startup of a drum boiler of a thermal power plant. The goal is to find a sequence of valves that reaches from an initial state to an objective state in the shortest time possible, while while reducing the impact on the lifetime of the components of the power plant. The simulation model is developed using OMEdit Modelica environment. The results of the proposed method outperform the time, avoiding situations of stress that endangers the components of the power plant, compared to a reference startup operation.

Keywords: Startup optimization, drum boiler, modelica, simulated annealing, thermal power plants

1. Introduction

Thermal power plants are a reliable source of electricity. To improve their competitiveness in the electricity markets, they must improve their operational procedures to be more efficient. Being one of the most important components of a thermal power plant, the drum boiler has the potential to improve the competitiveness of a thermal power plant by means of the reduction of its startup time. However, if startup is carried out too fast, excessive thermal stresses can occur in the drum boiler components. Therefore, the design and optimization of operational procedures must consider the physical constraints of the drum boiler to assure its integrity.

Much has been done on the optimization and control of operations of thermal power plants, specifically on the processes of the drum boiler of a thermal power plant. Some examples are the work of Franke, et al. [1], Kim and Choi [2] and Belkhir et al. [3].

Metaheuristic algorithms are very useful for finding good solutions when it comes to large combinatorial problems. Specially, the simulated annealing algorithm developed by Kirkpatrick, et al. [4] has proven to be effective for finding good solutions, avoiding falling into local optimum because of its "cooling" method.

In this paper, we propose the use of the simulated annealing algorithm with valve operation sequences represented as individuals of 3 chromosomes to find the optimal operating procedure for the startup of a drum boiler of a thermal power plant. The problem consists of finding a sequence of valves that takes the system from an initial state to a goal state in the shortest time possible, while reducing the impact on the lifetime of the components of the power plant.

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Because the effect of a valve operation on the process properties is time-related, dynamic simulation is needed in order to find the optimum operating procedure. Dynamic simulation is an area in which much work has been done (Zhang et al. [5], Aström and Bell [6] and Adam, et al [7]). In this paper, a drum-boiler dynamic simulator was developed using OMEdit Modelica environment.

To find the optimal operational procedures for the startup of a drum boiler we propose a methodology that integrates the the dynamic simulator with an optimization algorithm using simulated annealing

Nomenclature:

σ_D	thermal stress in the thick-walled
P	pressure inside the drum
P_{sat}	saturation pressure of the steam extracted from the drum
P_{goal}	goal pressure
$\dot{Q}$	heat flow
q_{goal}	goal steam mass flow
q_s	steam flow rate extracted from the drum
t	time
t_0	initial time
t_f	final time
V_{pos}	valve position of the steam outlet valve

2. Problem Statement

The startup of a drum boiler can be formulated as taking the system from an initial state to a goal state in a minimum time while satisfying a number of mechanical and process constraints. The initial and goal states are described in terms of local pressure and steam mass flow.

According to Belkhir, et al. [3], the general optimization problem for the drum boiler startup can be represented with the following equations:

$$\text{Min}\left((A * S) + \alpha\left(P_{sat} - P_{goal}\right)^2 + \beta\left(q_s - q_{goal}\right)^2\right) \quad where \quad S = \sum_{t_0}^{t_f} dt \tag{1}$$

Subject to:

$$0 \le V_{pos} \le 1 \tag{2}$$

$$0\ \frac{MW}{min} \le \frac{d\dot{Q}}{dt} \le 25\ \frac{MW}{min} \tag{3}$$

$$0 \le \dot{Q} \le 500\ MW \tag{4}$$

$$-10\ MPa \le \sigma_D \le 10\ MPa \tag{5}$$

Equation 1 seeks to minimize the time it takes for the drum boiler to reach the goal. When A = 0 the problem is reduced to find a sequence of operations that is feasible but not necessarily optimal [8]. A feasible solution is one that reaches the goal state without violating any of the constraints.

Equation 2 limits the opening of the steam outlet valve (V_{pos}) to values between 0 (totally closed) and 1 (fully open), while equation 3 ensures that the heat ($\dot{Q}$) per minute does not exceed 25 MW/min. Equation 4 is a constraint of the accumulated heat limit of the drum boiler which must not exceed 500 MW and equation 5 is a constraint that avoids an excessive thermal stress in the drum boiler that must be less than 10 MPa.

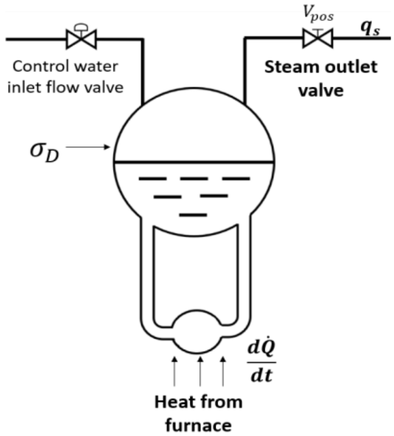

Fig.1. Schematic diagram of the drum boiler

Fig. 1 shows a schematic of the drum boiler. The heat is supplied in MW, the water is supplied by a control system and the steam flow is controlled by a valve. The interaction between the opening of the steam outlet valve and the heat flow in the drum boiler generates steam at pressure (P_{sat}) which exits at flow rate (q_s). The steam can later be sent to a superheater or directly to a steam turbine [6].

3. Methodology

To find the optimal operating procedures for the startup of a drum boiler we propose a methodology that combines dynamic simulation of the drum boiler with an optimization algorithm based on simulated annealing. Fig. 2 shows the methodology.

In order to evaluate the methodology, the dynamic simulator of the drum boiler was implemented on the OMEdit Modelica V 1.13 software and the optimization algorithm was developed using the R Studio platform. The interoperability was made possible through commands sent via the command-line and sharing data stored in text files (.txt) and comma-separated values files (.csv).

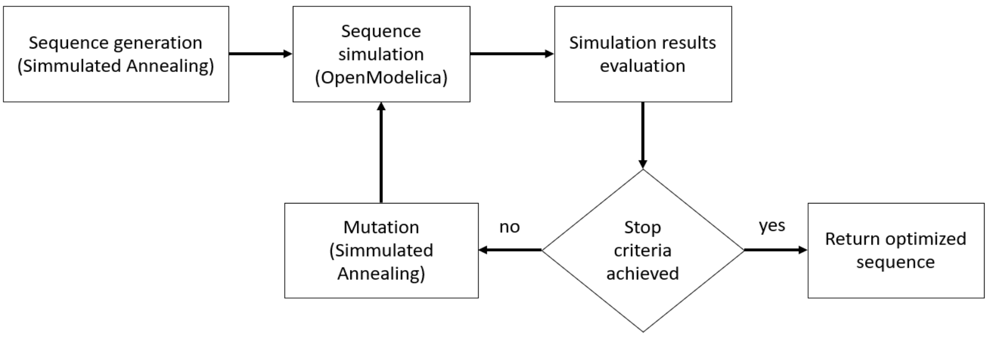

Fig. 2. Proposed methodology for obtaining optimum operating procedures for the startup of a drum boiler

3.1. Simulation model

The model for the simulation of the drum boiler is based on Aström and Bell [6]. The liquid level is controlled by means of a PI controller that operates the water pump. The model calculates the dynamic values of saturation pressure, steam flow rate and thermal stress, given an operation sequence composed of operation time, steam outlet valve position and heat flow. Fig. 3 shows the model of the drum boiler for the simulator software.

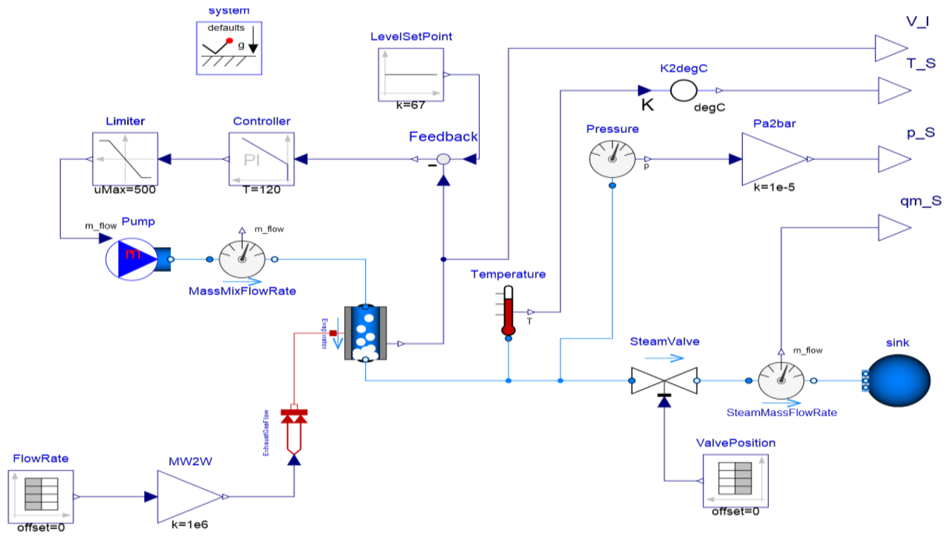

Fig.3. Simulation model graphical representation in the OMEdit Modelica V 1.13 software

3.2. Simulated annealing algorithm

To solve the dynamic optimization problem, we propose the algorithm shown in Fig. 4. The first step is to generate a feasible random operation sequence that will serve as a seed. The seed is fed to the simulated annealing algorithm that consists in evaluating the *actual* solution (S_a). Based on this individual, a *candidate* solution (S_c) is generated by applying a series of mutations (see Section 3.4). Then the candidate solution is also evaluated and compared against the actual solution. If the candidate solution is better than the actual solution, the candidate solution becomes the actual solution. Otherwise, the "worst" *S*c can be selected if a randomly generated number is less than an acceptance probability. The acceptance probability is calculated using an energy function that depends on the iteration-varying parameter called *temperature*. Temperature is set high at the beginning and decreases with the execution of the algorithm. As the temperature is reduced the probability of accepting worse solutions decreases. Thus, this scheme provides the algorithm the ability to jump out any possible local optima and then focus on the region where the true optimum can be located. The optimization algorithm was implemented in the R language.

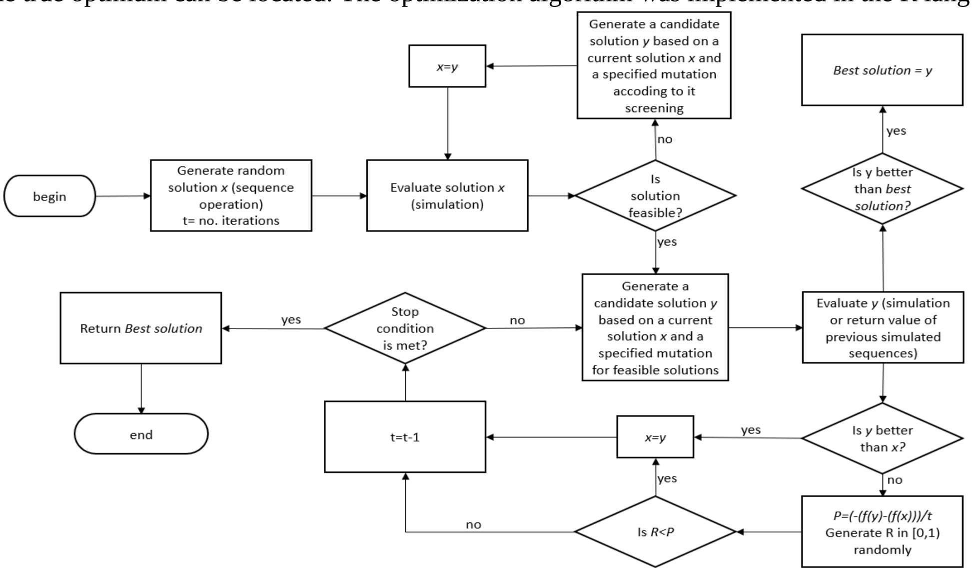

Fig. 4. Proposed optimization algorithm

3.3. Solution representation

The solution is represented by means of a 3-chromosome structure. The first chromosome represents the sequence of valve actions. The second chromosome represents the execution time per action and the third chromosome represents the number of times that the same action is repeated. Each element in the first chromosome is an integer that represents a combination of the valve position of the steam outlet valve and the heat flow, according to Table 1.

Table1. Combinations of heat flow and V_{pos} of each action

Action	$d\dot{Q}/dt$	V_{pos}
1	8	0
2	8	0.6
3	8	1
4	16	0
5	16	0.6
6	16	1
7	24	0
8	24	0.6
9	24	1

Fig 5 shows an example sequence of operations using the 3-chromosome structure. Each position has a time that can be 60, 120 or 180 seconds.

3.4. Generation of the neighborhood

The neighborhood refers to candidate solutions generated from the actual solution. Candidate solutions are created by means of a mutation operator. The mutation consists of changing a random position of time for a random time, changing a random position of action for a random action and changing a random position of repetition for a random number of repetitions. The double mutation consists of changing two random positions of time for two random times, changing two random positions of action for two random actions and changing two random positions of repetition for two random numbers of repetition and so on.

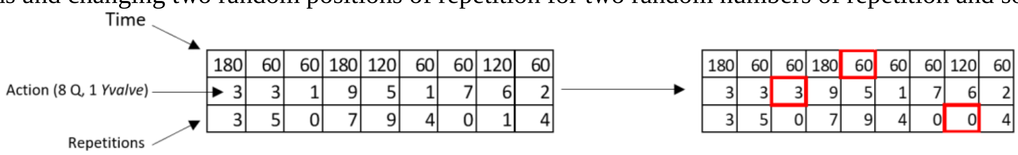

Fig. 5. Sequence operation in a scheme of 3 chormosome and representation of the mutation

A candidate solution is created after applying one or more mutations to a copy of the actual solution. The number of mutations is determined by the goodness-of-fit. The goodness-of-fit is a function of number of times the startup process went out of the thermal stress margin, an evaluation of constraint of the accumulated heat limit of the drum boiler and the objective function. The smaller the goodness-of-fit, the greater the number of mutations, according to Table 2.

Table 2. Number of mutations according to the goodness-of-fit of the sequence

Goodness of fit	Number of mutations
1/200	6
1/100	4
1/50	3
1/20	2
<=1/20 or feasible	1

4. Experiments and Results

To test the algorithm, the goal was set to Pgoal = 90 bar, qgoal= 180 kg/s. The weights were set to $\alpha = 10^{-4}$ and $\beta = 10^{-4}$. Parameter A was set to 0 for obtaining the seed explained in Section 3.2 and then changed to 1 when used in the rest of the algorithm.

A run of 2000 iterations was carried out, in which 1176 drum boiler simulations took place. The reason the number of simulations does not match the number of iterations is because the algorithm avoided simulating repeated sequences. It took the computer approximately 7 hours of processing time on a Windows 10 pro computer, with 4.00GHz Intel Xeon W-2125 CPU and 32GB of RAM.

Fig. 6 shows the objective function evaluation through iterations of the proposed algorithm. It can be seen that the first iterations produce infeasible albeit diverse solutions. After iteration 492, as more feasible solutions are found, the results become less disperse leading to a possible optimum result that satisfies all constraints.

Fig. 7 shows the convergence of the qualification of the sequences, according to his evaluation in the simulator. This rating depends on time, proximity to objective pressure and flow, and violation of constraints. This figure clearly shows the point at which the algorithm found its best solution.

As shown in Fig. 8, the startup duration obtained with our proposal (1600 seconds) contrasts with the result obtained with the reference startup procedure that takes 2700 seconds to reach the goal.

One of the reasons why this occurs is because the sequence obtained by the simulated annealing algorithm takes advantage of the different options of heat flow and valve opening to reach the target in less time, without violating the constraints.

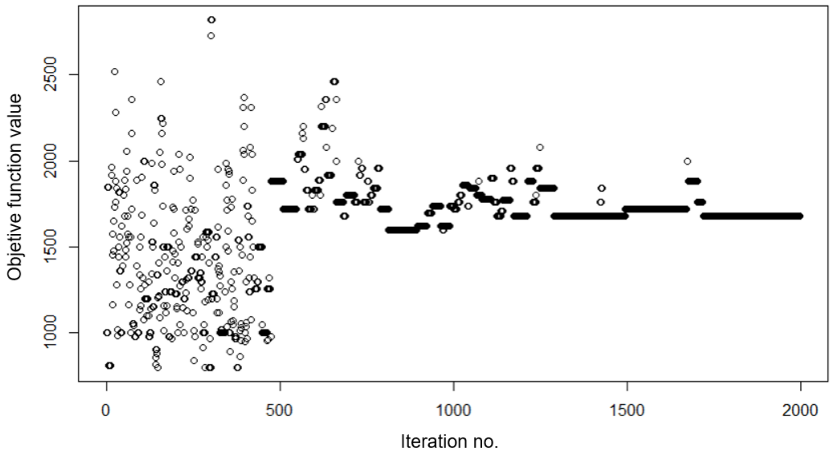

Fig. 6. Objective function evaluation through iterations of the optimization algorithm.

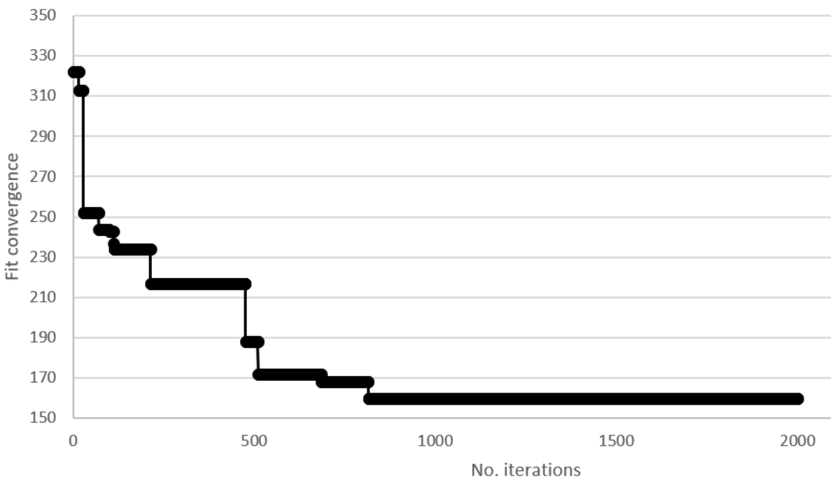

Fig. 7. Convergence of the solutions obtained by the optimization algorithm.

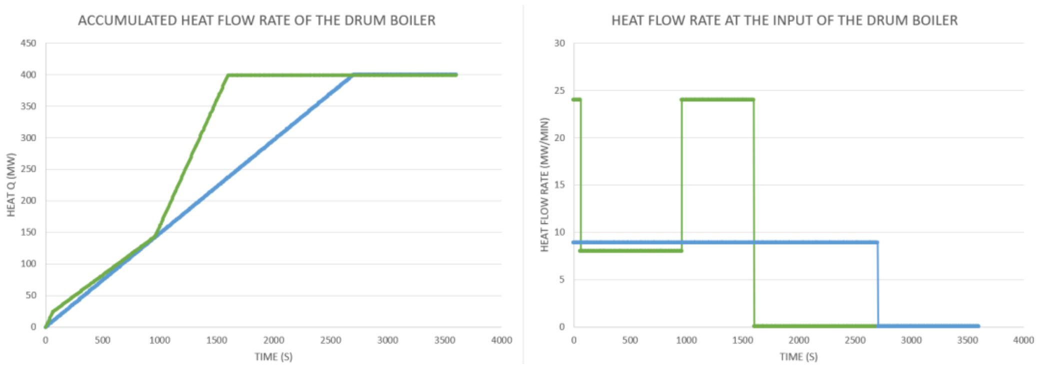

Fig. 8. Comparison of the reference startup profile reported by Aström et al. [6] (blue line) and the startup profile obtained with the proposed algorithm (green line)

5. Conclusions and Future Work

In this paper, we proposed a simulated annealing algorithm to find the optimal operation sequence for the startup of a drum boiler of a thermal power plant. With this approach it was possible to speed up the startup by 40.7%, in comparison to the reference procedure. Not only a fastest startup was obtained but also the startup procedure ensures the integrity of the equipment by reducing the impact on the lifetime of the equipment.

As future work, we will compare the proposed algorithm against other metaheuristic algorithms.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Emilio Garduno developed the experiments, wrote the paper and conducted the research; Miguel Angel Zuniga-Garcia and Erik Rosado-Tamariz, stated the methodology and supervised the research process, Rafael Batres supervised the research process and helped to obtain funding; all authors had approved the final version.

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