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A MODEL OF PROCESS STEAM NETWORK IN A STEEL PLANT WITH IDENTIFICATION OF PARAMETERS BY A GENETIC ALGORITHM

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Abstract: This paper proposes a mathematical model of a process steam distribution network, with parameters set through a genetic algorithm, with the purpose of maximizing the energy utilization in a steel plant. The model is based on thermodynamics principles, including the balance of mass and energy. To determine the model parameters, due the dependencies between the equations, a genetic algorithm was applied. Once the control systems are not usually interconnected, steam pressure oscillations may occur in the Coke Plant side or in the Utilities Sector resulting in a large amount of wasted steam through independent relief systems. On a steel plant, steam can be used for some specific equipment's or processes. In general, steam is considered a power source, applied on heating and power plants for electricity generation. Avoiding the steam waste is possible to improve the energy utilization figures resulting in both financial and environmental gains.
Keywords - Process Steam Distribution, Modelling, Coke Plant, Utilities Plant, Genetic Algorithm, Energy Saving

INTRODUCTION

A large amount of energy from byproduct gases, steam and electricity, is produced and recovered in the steelmaking process. It accounts for 50% - 60% of the gross energy consumption of the steelmaking process (ZHANG, 2011), presenting sometimes an imbalance between production and consumption at different points in the steam distribution network. Since this network does not have a centralized control, this imbalance causes the opening of relief valves, culminating in steam emissions into the atmosphere.

Papers such as (ZHANG, 2011), (SONG, 2011) and (Junior, 2016) demonstrate how to achieve the best distribution in the recovery of gases generated in the coke plant processes (COG), Steelmaking (LDG) and Blast Furnaces (BFG), including steam generated and extracted from the boilers in the Utilities area. However, the generation of steam in the CDQ (CDQ - Coke Dry Quenching), located in the Coke Plant area, and the mass and energy balance of steam generated in the Utilities Plant are not treated in detail.

Inside an integrated steel plant, in terms of steam generation, we can highlight the Coke Plant, more precisely in the Coke Dry Quenching area (CDQ - Coke Dry Quenching) and the Utilities Sector, with a focus on steam boilers designed for electricity generation. The CDQ process is illustrated in Figure 1.

The coke cooling process is carried by blowing the cooling gas at the bottom of the chamber, passing through a distribution system, and rising toward the top, absorbing heat from the coke and reaching the temperature of approximately 800 ° C. The gas is collected by 32 channels, arranged around the upper part of the chamber, and directed through a primary collector where larger particles are retained. Then the gas is fed into the boiler where steam is produced due the heat transfer between the gas and water (ABM, 2003).

In the Utilities Sector, the process is shown in Figure 2.

The COG (Coke Oven Gas) generated in the coke batteries, LDG (Linz-Donawitz Gas) generated in Steelmaking and BFG (Blast Furnace Gas) generated in the Blast Furnaces are transported to the boilers where its calorific power is harnessed to heat water and generate steam. Basically, the steam produced in the boilers is intended for the turbines, for electricity generation, but is possible to reduce this generation and assign the steam to other consumers when necessary.

Despite the connection between the steam pipes between the plants (Coke Plant and Utilities Sector), they have

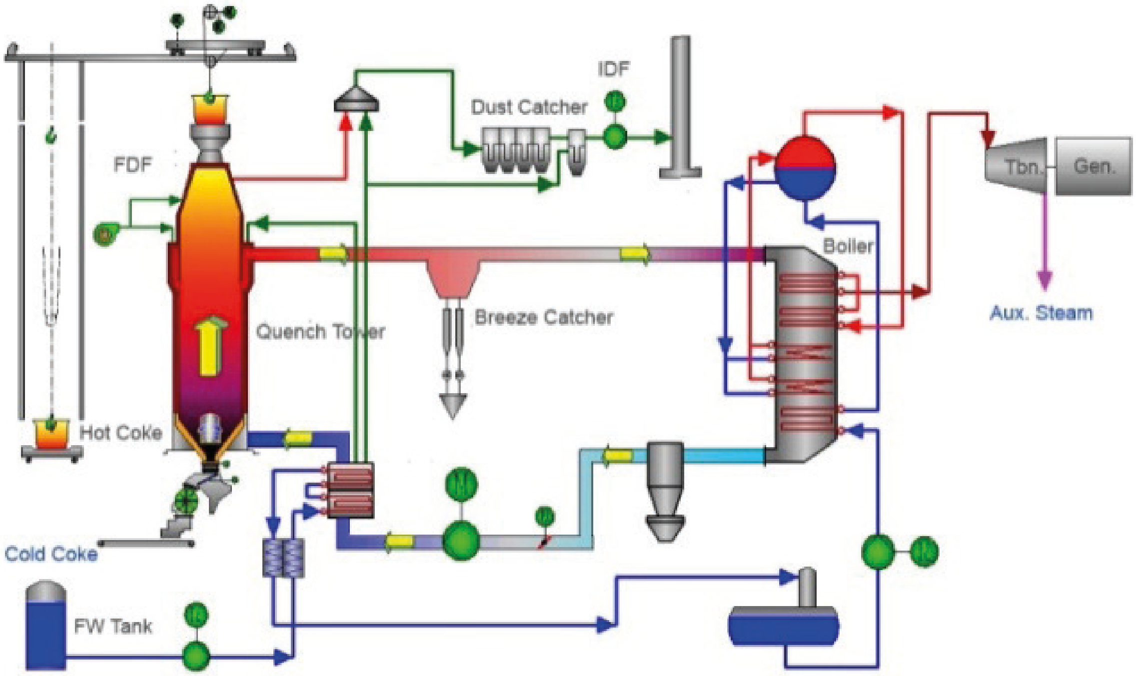

Figure 1. Coke Dry Quenching - CDQ (CHINA STEEL, 2015).

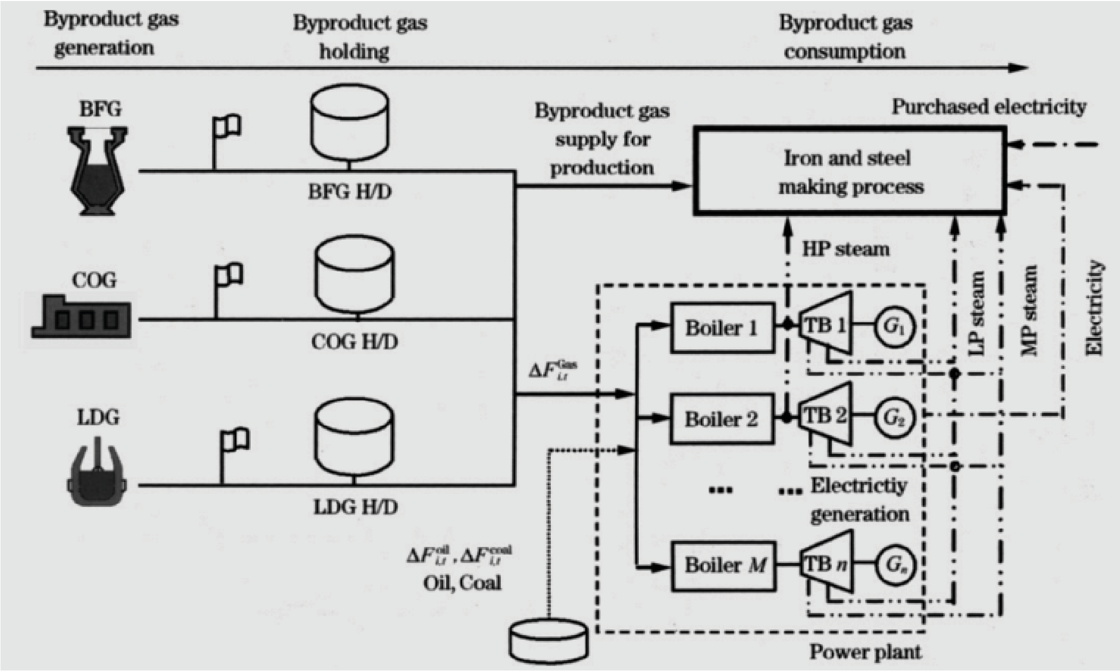

Figure 2. Generation of steam in boilers (ZHANG, 2011)

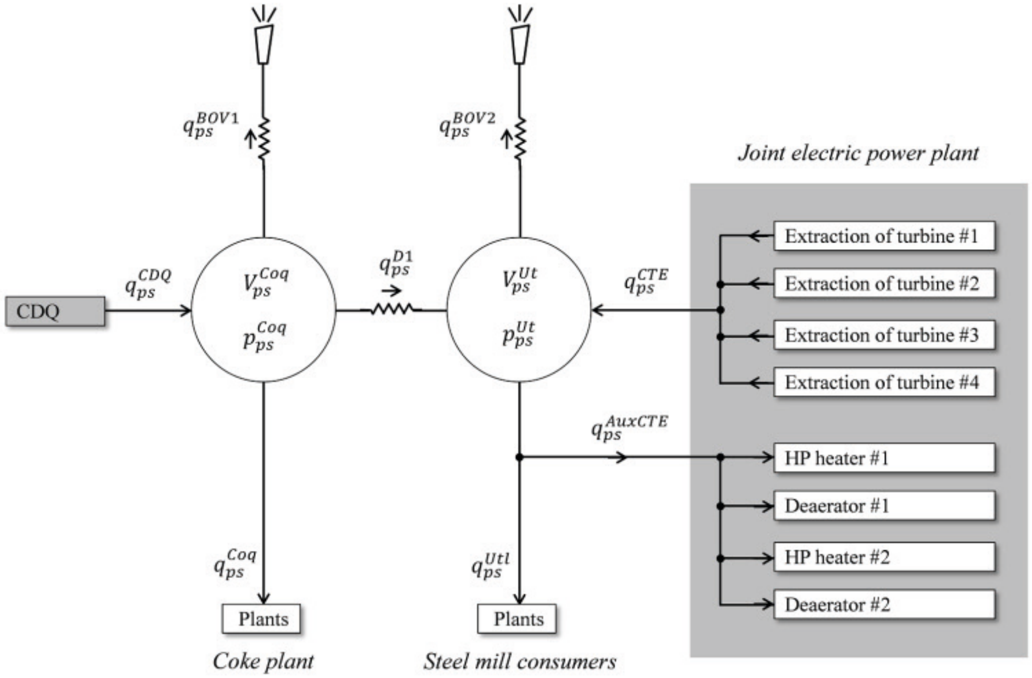

Figure 3. Simplified Steam Balance Model

independent controls, turning the balance between production and consumption, a major challenge. In some cases, while CDQ discards steam to the atmosphere, the steam for the turbines is being extracted (reduction of electricity generation), to supply other consumers, causing an inefficient use of steam.

Aiming to anticipate control actions to prevent any loss of steam and maximize the electricity production, we propose a model of the steam distribution network. The model uses as input, current flows of steam consumption and generation to estimate the pressure variations in future instants of time.

This article is organized around 5 sections. Section 2 describes the steam balance model and its mathematical deduction. Section 3 presents de genetic algorithm and the model fitting results are presented in Section 4. Section 5 is reserved for the conclusions, relevant considerations and future developments.

THE STEAM BALANCE MODEL

The steam distribution network on an integrated steel mill is usually fed by the steam extracted from the power plant's boilers and by the steam from CDQ.

Considering the mass and energy balance, the distributed nature of the process will be modeled in concentrated volumes, as shown in Figure 3.

In the model presented in Figure 3, based on (ÅSTRÖM, 2000) and (OLIVEIRA JUNIOR, 2009), V represents volume, ρ density, h specific enthalpy, T temperature, p pressure, and q is the mass flow rate. The subscripts ps, m and w indicate respectively process steam, water and metal. The subscript t is used to indicate the total amount, which refers to the system. The *Coq* and *Utl* superscripts indicate, respectively, quantities related to the process steam distribution network from Coke Plant and Utilities Sector side.

It is considered that there is a flow restriction between the concentrated volumes e, so that it is possible to have different pressures in each volume.

The overall mass balance is given by:

$$\frac{d}{dt}\left(\rho_{ps}^{Coq}V_{ps}^{Coq} + \rho_{ps}^{Utl}V_{ps}^{Utl}\right) = \left(q_{ps}^{CDQ} + q_{ps}^{CTE}\right) - \left(q_{ps}^{Coq} + q_{ps}^{Utl}\right) \quad (1)$$

The overall energy balance is given by:

$$\frac{d}{dt}\left[\rho_{ps}^{Coq}u_{ps}^{Coq}V_{ps}^{Coq} + \rho_{ps}^{Utl}u_{ps}^{Utl}V_{ps}^{Utl} + m_m^{Coq}c_m^{Coq}T_m^{Coq} + m_m^{Utl}c_m^{Utl}T_m^{Utl}\right] = \left(q_{ps}^{CDQ} - q_{ps}^{Coq} - q_{ps}^{D1}\right)h_{ps}^{CDQ} + \left(q_{ps}^{D1} + q_{ps}^{CTE} - q_{ps}^{Utl}\right)h_{ps}^{Utl} \quad (2)$$

where:

- ρ_{ps}^{Coq} and ρ_{ps}^{Utl} are the process steam density values [kg/m^3];

- u_{ps} is the internal process steam energy [kJ/kg], and can be rewritten as follows:

$$u = h - \frac{P}{\rho}$$

- h_{ps} is the process steam enthalpy [kJ/kg];

- V_{ps}^{Coq} and V_{ps}^{Utl} are the steam distribution network pipes internal volumes [m^3];

- m_m^{Coq} and m_m^{Utl} are the steam distribution network pipes mass values [kg];

- c_m is the pipe metal specific heat value [kJ/kg°C];

- t_m is the pipe metal temperature [°C];

- q_{ps}^{CDQ} is the total steam flow received from CDQ [kg/s];

- q_{ps}^{Coq} is the total steam flow consumed in the Coke Plant [kg/s];

- q_{ps}^{CTE} is the total steam flow received from the Power Plant [kg/s];

- q_{ps}^{Utl} is the total steam flow consumed by the distribution network consumers [kg/s];

- q_{ps}^{D1} is the total steam flow in the desuperheater which is responsible for the steam transfer between the Coke

Plant and Utilities Sector [kg/s];

The following considerations are also applied in the model:

1. Steam, water and metal are in thermal equilibrium. Therefore T_m (metal temperature) is considered equal to T_s (steam saturation temperature).

2. The variables ρ_{ps}^{Coq} and ρ_{ps}^{Utl} can be written as a function of the steam pressure considering that the whole system is in saturated state and the pressure has the same value in all points inside the concentrated volume. Then:

$$\frac{d\rho_{\text{ps}}}{dt} = \frac{\partial \rho_{\text{ps}}}{\partial t}\frac{dp_{ps}}{dt} \quad (4)$$

3. There are no volume variations inside the pipes along the time. Then:

$$\frac{dV_{\text{ps}}^{Coq}}{dt} = 0 \xrightarrow{and} \frac{dV_{\text{ps}}^{Utl}}{dt} = 0 \quad (5)$$

From (1) and (2):

$$e_{11}\frac{dp_{ps}^{Coq}}{dt} + e_{12}\frac{dp_{ps}^{Ut}}{dt} = q_{ps}^{CDQ} + q_{ps}^{CTE} - q_{ps}^{Coq} - q_{ps}^{Ut} \quad (6)$$

$$e_{21}\frac{dp_{ps}^{Coq}}{dt} + e_{22}\frac{dp_{ps}^{Ut}}{dt} = h_{ps}^{Coq}\left(q_{ps}^{CDQ} - q_{ps}^{Coq} - q_{ps}^{D1}\right) + h_{ps}^{Ut}\left(q_{ps}^{D1} + q_{ps}^{CTE} - q_{ps}^{Ut}\right) \quad (7)$$

Where:

$$e_{11} = V_{ps}^{Coq}\frac{\partial \rho_{ps}^{Coq}}{\partial p_{ps}^{Coq}} \quad (8)$$

$$e_{12} = V_{ps}^{Ut}\frac{\partial \rho_{ps}^{Utl}}{\partial p_{ps}^{Coq}} \quad (9)$$

$$e_{21} = \left(\frac{\partial \rho_{ps}^{Coq}}{\partial p_{ps}^{Coq}} h_{ps}^{Coq} + \rho_{ps}^{Coq}\frac{\partial h_{ps}^{Coq}}{\partial p_{ps}^{Coq}}\right) V_{ps}^{Coq} - V_{ps}^{Coq} + m_m^{Coq} c_m^{Coq}\frac{\partial T_m^{Coq}}{\partial p_{ps}^{Coq}} \quad (10)$$

$$e_{22} = \left(\frac{\partial \rho_{ps}^{Utl}}{\partial p_{ps}^{Utl}} h_{ps}^{Utl} + \rho_{ps}^{Utl}\frac{\partial h_{ps}^{Utl}}{\partial p_{ps}^{Utl}}\right) V_{ps}^{Utl} - V_{ps}^{Utl} + m_m^{Utl} c_m^{Utl}\frac{\partial T_m^{Utl}}{\partial p_{ps}^{Coq}} \quad (11)$$

Rewriting, making it a discrete function and applying some conversion factors to adjust the measurement units, we obtain the final equations (12) and (13):

$$p_{ps}^{Coq}\left((k+1)T\right) = p_{ps}^{Coq}(kT) + \frac{K_q}{K_p}T\begin{bmatrix} p_{11}q_{ps}^{CDQ}(kT) + p_{12}q_{ps}^{CTE}(kT) \\ +p_{13}q_{ps}^{Coq}(kT) + p_{14}q_{ps}^{Utl}(kT) \\ +p_{15}q_{ps}^{D1}(kT) \end{bmatrix} \quad (12)$$

$$p_{ps}^{Utl}\left((k+1)T\right) = p_{ps}^{Utl}(kT) + \frac{K_q}{K_p}T\begin{bmatrix} p_{21}q_{ps}^{CDQ}(kT) + p_{22}q_{ps}^{CTE}(kT) \\ +p_{23}q_{ps}^{Coq}(kT) + p_{24}q_{ps}^{Utl}(kT) \\ +p_{25}q_{ps}^{D1}(kT) \end{bmatrix} \quad (13)$$

Where:

Kp=98,0665 [kPa/(kgf/cm^2)] is a pressure conversion factor from [kgf/cm^2] to [kPa] and $K_q = \left(\frac{1000}{3600}\right)$=0,27777 [(kg/s)/(t/h)] is a flow conversion factor from [t/h] to [kg/s].

$$p_{11} = \frac{e_{22} - e_{12}h_{ps}^{Coq}}{e_{11}e_{22} - e_{12}e_{21}} \quad (14)$$

$$p_{12} = \frac{e_{22} - e_{12}h_{ps}^{Utl}}{e_{11}e_{22} - e_{12}e_{21}} \quad (15)$$

$$p_{13} = \frac{e_{12}h_{ps}^{Coq} - e_{22}}{e_{11}e_{22} - e_{12}e_{21}} \quad (16)$$

$$p_{14} = \frac{e_{12}h_{ps}^{Utl} - e_{22}}{e_{11}e_{22} - e_{12}e_{21}} \quad (17)$$

$$p_{15} = \frac{e_{12}h_{ps}^{Coq} - e_{12}h_{ps}^{Utl}}{e_{11}e_{22} - e_{12}e_{21}} \quad (18)$$

$$p_{21} = \frac{(e_{11}e_{22} + e_{12}e_{21})h_{ps}^{Coq} - e_{21}e_{22}}{(e_{11}e_{22} - e_{12}e_{21})e_{22}} \quad (19)$$

$$p_{22} = \frac{e_{11}h_{ps}^{Utl} - e_{21}}{e_{11}e_{22} - e_{12}e_{21}} \quad (20)$$

$$p_{23} = \frac{e_{21} - e_{11}h_{ps}^{Coq}}{e_{11}e_{22} - e_{12}e_{21}} \quad (21)$$

$$p_{24} = \frac{e_{21} - e_{11}h_{ps}^{Utl}}{e_{11}e_{22} - e_{12}e_{21}} \quad (22)$$

$$p_{25} = \frac{e_{11}\left(h_{ps}^{Utl} - h_{ps}^{Coq}\right)}{e_{11}e_{22} - e_{12}e_{21}} \quad (23)$$

The following units are now applied:

- Mass: kg;
- Pressure: kgf/cm^2;
- Temperature: ºC;

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- Entalphy: kJ/kg;
- Specific Mass: kg/m³;
- Flow: t/h;
- Sampling time: s.

WATER STEAM PROPERTIES

The water steam properties can be calculated as a pressure function. For the saturated steam thermodynamic properties, polynomial functions (27), (28) and (29) were approximated from Table I.

Pressure [kg/cm²(g)]	Temp. [°C]	r_s [m³/kg]	h_s [kJ/kg]
10,0	183,34	5,54939	2779,1
11,0	187,21	6,03027	2782,2
12,0	190,83	6,50999	2784,9
13,0	194,24	6,99007	2787,3
14,0	197,47	7,46993	2789,4
15,0	200,53	7,94976	2791,3
16,0	203,45	8,43028	2792,9
17,0	206,24	8,91107	2794,4
18,0	208,91	9,39144	2795,7
19,0	211,47	9,87264	2796,8
20,0	213,94	10,35497	2797,9
21,0	216,32	10,83752	2798,7
22,0	218,61	11,32144	2799,5

TABLE I. STEAM PROPERTIES (COLLONA, 2004)

Functions from Table I:

$$T_s = -0{,}0688p_s^2 + 5{,}1117p_s + 139{,}28 \quad (24)$$

$$\rho_s = 0{,}4808p_s + 0{,}7399 \quad (25)$$

$$h_s = -0{,}1006p_s^2 + 4{,}8752p_s + 2740{,}7 \quad (26)$$

$$\frac{\partial T_s}{\partial p_s} = -0{,}1376p_s + 5{,}1117 \quad (27)$$

$$\frac{\partial \rho_s}{\partial p_s} = 0{,}4808 \quad (28)$$

$$\frac{\partial h_s}{\partial p_s} = -0{,}2012p_s + 4{,}8752 \quad (29)$$

PARAMETERS DETERMINATION

The model uses the actual values of pressure and current flows to predict the pressure at future times, however, since parameters as enthalpy, specific weight and temperature have been determined according to the actual pressure, is necessary to find the metal mass and volume values of the existing steam pipes in both systems (Coke Plant and Utilities Sector). Although these are physical parameters of existing pipes, its measurement is difficult due to the long extension (over 20 km) and the many branches of the process steam distribution network. These parameters can be easily noticed in the both (1) and (2). Once they represent quantities of the actual installations, it is not only necessary to provide a good model fit, but the estimated values of these parameters must also be kept within certain limits for consistency with reality.

To estimate these parameters and validate the model, a genetic algorithm was developed, using as input measured signals sampled over a period of 24 hours with a sampling interval of 15 [s] as shown in the Figure 4 to Figure 10.

THE GENETIC ALGORITHM

Genetic algorithms are very useful for two distinct and comprehensive purposes: the selection of parameters for the performance optimization of a system and the validation and adjustment of quantitative models (CHAMBERS, 2001).

In this work a genetic algorithm is applied in order to select the best metal mass values (m_m^{Coq} and m_m^{Utl}) and volumes (V_{ps}^{Coq} and V_{ps}^{Utl}) to adjust the steam balance model presented, and achieve the lowest possible error between measured and calculated values of steam pressure.

Observing (6) to (23) it is possible to realize there is a relation between the Coke Plant and Utilities Plant systems. For this reason and because it is a four-variable adjustment, a genetic algorithm was selected to be applied.

GENETIC ALGORITHM APPLICATION

Intending to restrict the possible solutions to industrial realistic values, the genetic algorithm application was separated in two phases.

In the first phase an "equivalent pipe" concept is introduced, considering all pipes with the same diameter. Then it is possible to calculate proportional mass and volume values according the pipe total length.

For the second phase, the genetic algorithm is applied once again, now in a conventional manner, aiming to find mass and volume values to adjust the model. However, these values shall be limited to a ± 20% variation from the values found in the first phase.

As resources, the mathematical software MATLAB R2013a was used, installed on a virtual machine running Windows XP, hosted by a MacBook-Pro I5 with 8Gb of RAM.

GENETIC ALGORITHM ARCHITECTURE

The simplified genetic algorithm flow chart can be evaluated from the Figure 11.

The first step is where the restrictions and general conditions are defined. Then the initial population is generated, and each chromosome is evaluated through a fitness function. In this case, the model equations itself are applied to generate calculated pressure values and compare them to the measured values using the *compare* function, available in MATLAB. The *compare* function output is a grade between 0 and 100% which represents the *fitness* (percentage adjustment value) of each chromosome.

During the *crossover* step, as in (CHAMBERS, 2001) and (ALMEIDA, 2015), the *fitness* value is used to determine the selection potential of each individual. The selection process is nominated as *roulette wheel method,* mentioned in (CHAMBERS, 2001) and (ALMEIDA, 2015), and consists on an adaptive choosing model accordingly to its fitness value.

After crossing a pair of chromosomes, one or more elements of the new individuals may suffer a mutation. It happens when an element mutation rate reaches randomly a value less than the base mutation rate of 0.2%.

These new chromosomes are reevaluated, and their *fitness* is compared to the optimal stored values. The best fitting chromosomes of each epoch are stored.

PREMISSES

The maximum epoch iteration was limited to one hundred epochs. The chromosome format was kept in real numbers without binary codification. In this case, the information treatment is much more intuitive and less computational resources are needed.

CROSSOVER RATE AND MUTATION RATE

The crossover rate was fixed in 80%, and a *simple arithmetic crossover* was applied as in (CHAMBERS, 2001). The mutation rate was fixed and limited in 0.2%, where both *uniform and multiple uniform mutations* may happen randomly as in (CHAMBERS, 2001).

INITIAL POPULATION AND FITNESS FUNCTION

After some tests comparing speed and computational efforts, the initial population was defined by 50 random chromosomes arranged as $[V_{ps}^{Coq} m_m^{Coq} L^{Coq} V_{ps}^{Utl} m_m^{Utl} L^{Utl}]$ in phase one, where L^{Coq} and L^{Utl} are pipes lengths, and $[V_{ps}^{Coq} m_m^{Coq} V_{ps}^{Utl} m_m^{Utl}]$ in phase two.

For each chromosome applied in the model equations, there are several calculated steam pressure values. These values are compared with the measured values trough

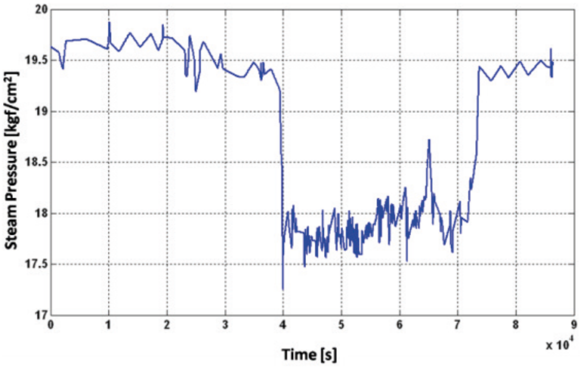

Figure 4. Coke Plant measured pressure

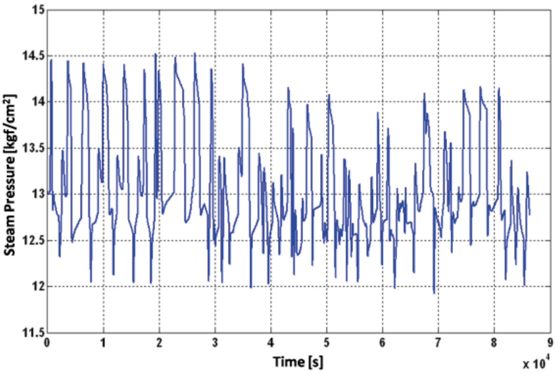

Figure 5. UtilitiesSector measured pressure

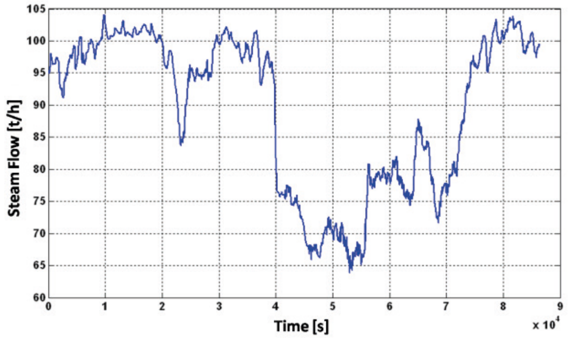

Figure 6. Generated steam flow measured in CDQ

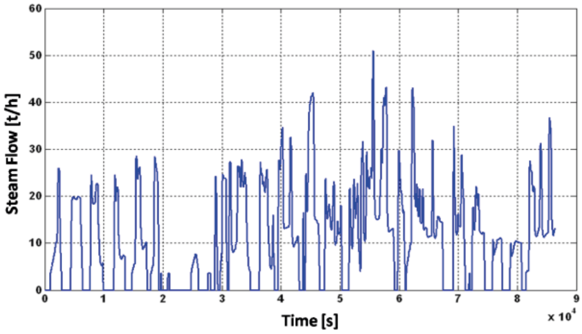

Figure 7. Generated steam flow measured in Power Plants

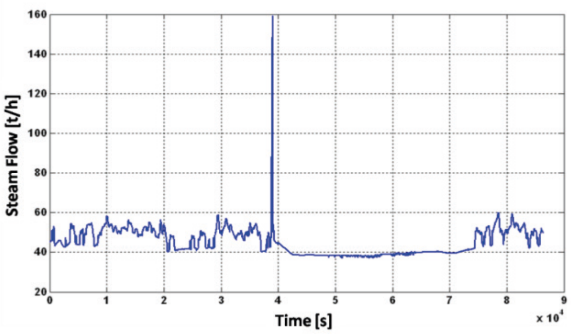

Figure 8. Consumed steam flow measured in Coke Plant

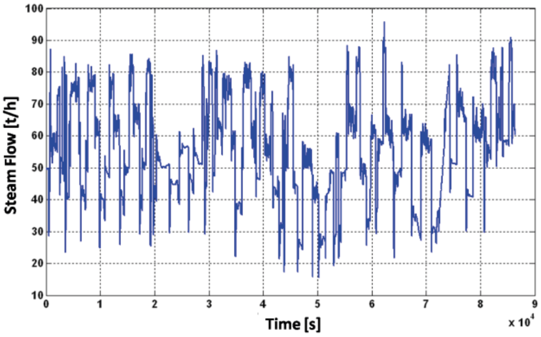

Figure 9. Consumed steam flow measured in Utilities Sector

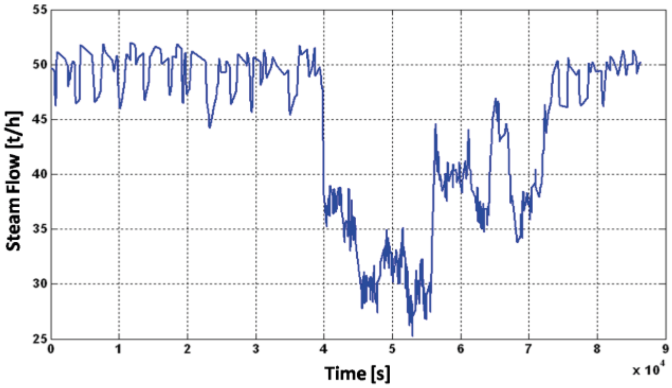

Figure 10. Consumed steam flow measured in Dessuperheater

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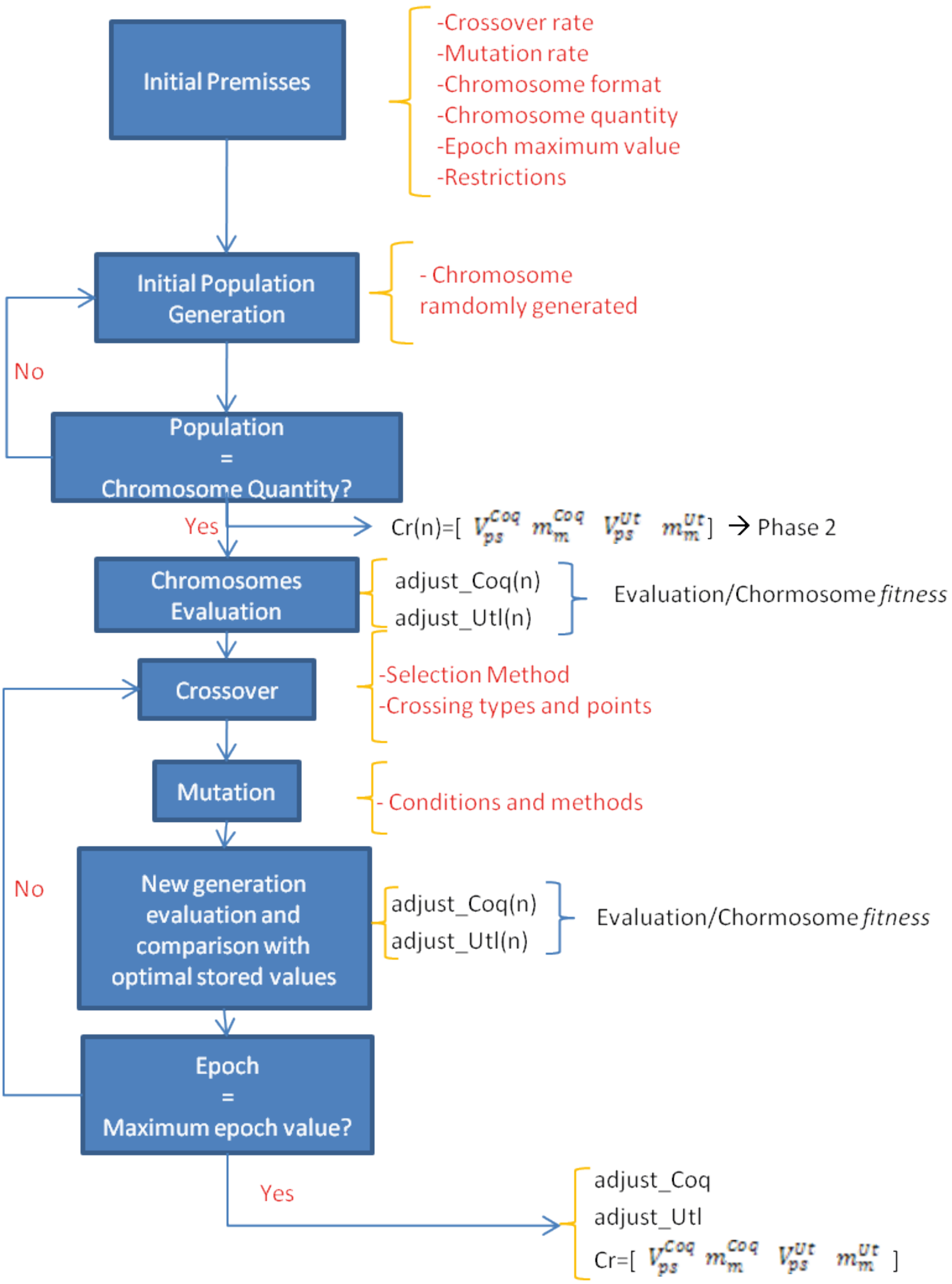

Figure 11. Proposed Genetic Algorithm Flow Diagram

the MATLAB *compare* function, which uses the root mean square error as a reference. Once the main objective is to reach 100% of adjustment factor, an adjustment value for the Coke Plant side and for the Utilities Sector side is generated for each individual.

CROSSOVER

Using the *roulette wheel method, according* (CHAMBERS, 2001) and (ALMEIDA, 2015), the chromosomes with higher fitness values will present higher probabilities to perform the crossover. In phase one the cross point is fixed and previously defined, while in phase two its randomly chosen among five possible combinations as shown in Figure 12.

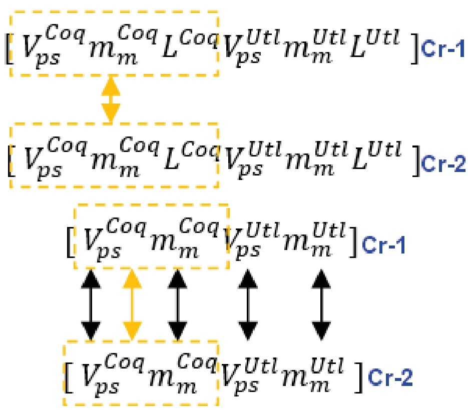

Figure 12. Phase 1 and 2 crossover possible combinations

MUTATION

Each chromosome has a probability of 0.2% of having one of its elements modified. In phase one the mutation affects directly the pipe length, which makes new proportional mass and volume values. During phase two, mutation can affect any chromosome element, regarding the values limits from the initial generation.

NEW GENERATION EVALUATION

The new generation is evaluated in the same manner as the initial population. Once the adjustments values are obtained, they are compared with the optimal values previously stored. With a previously fixed elitism, some of the best chromosomes from the last generation are direct passed to the new generation.

MODEL VALIDATION

After the genetic algorithm phase one, the adjustment values achieved were 97.51% in the Coke Plant side and e 90.78% in the Utilities Sector side as shown in Figure 13.

Mass, volume and length values achieved from phase one were:

$$V_{ps}^{Coq} = 389.3\ [m^3] \qquad V_{ps}^{Utl} = 987\ [m^3]$$

$$m_m^{Coq} = 442.4\ [ton] \qquad m_m^{Utl} = 1122\ [ton]$$

$$L^{Coq} = 7657\ [m] \qquad L^{Utl} = 19410\ [m]$$

In phase 2, the results were 97.73% in the Coke Plant side and 91,96% in the Utilities Plant side as shown in Figure 14.

Then, the final values for mass and volume achieved were:

$$V_{ps}^{Coq} = 446{,}1\ [m^3] \qquad m_m^{Coq} = 379.57\ [ton]$$

$$V_{ps}^{Utl} = 852{,}1\ [m^3] \qquad m_m^{Utl} = 1266\ [ton]$$

With these parameters values, the final fitness for the model in the Coke Plant side was 95.7% and in Utilities Sector was 82.4%, shown respectively in Figure15 and Figure 16.

CONCLUSION

The proposed model for steam distribution network and the identification of parameters using a genetic algorithm, produced results fully consistent with measured data of a steel plant. The model can provide good forecasts of a process steam network pressure for a prediction horizon up to 45s. The final fit results have also good repeatability when the parameters are applied with different sets of measured data. It is important to mention that the measured values lack of precision and invalid data effects was minimized by the application of a moving average technique during the final fitness evaluation.

It's relevant to mention that the variation presented in the approaching curves according Figure 13 and Figure 14 are introduced by the mutation and crossover steps during the genetic algorithm execution. Due to these steps, the population fitting average can change according to the values combinations and modifications.

This model will allow the pressure validation of a future optimization algorithm, aiming to reduce the steam mass balance instability and minimize the current process steam energy losses, enabling a more efficient operation of steel plants.

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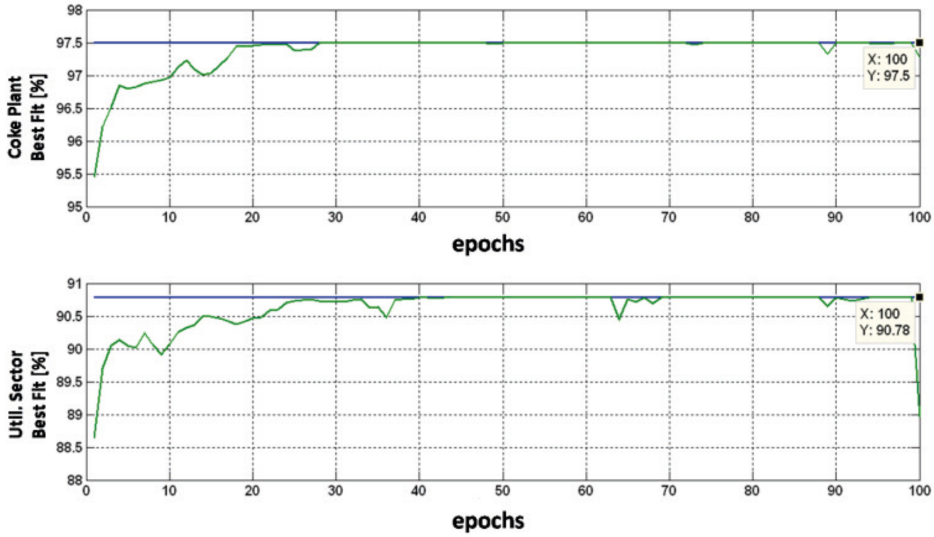

Figure 13. Phase 1 fitness results

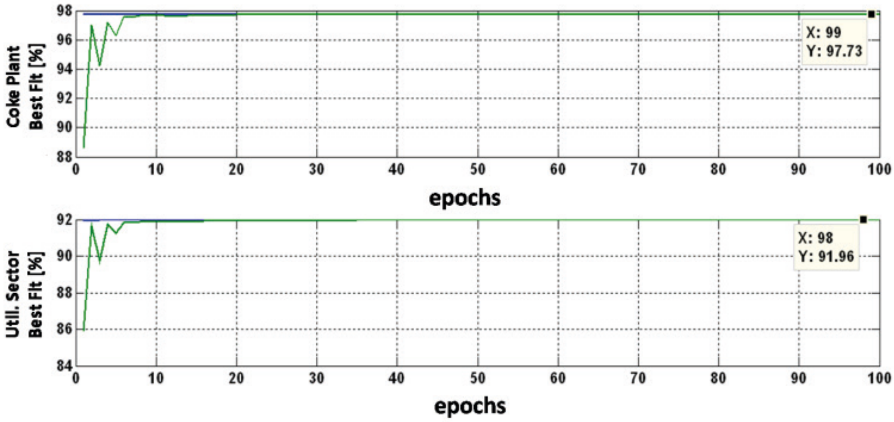

Figure 14. Phase 2 fitness results

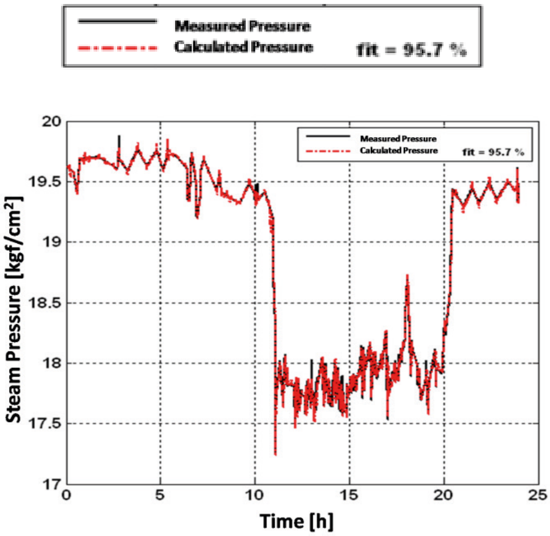

Figure 15. Coke plant side pressure fitness

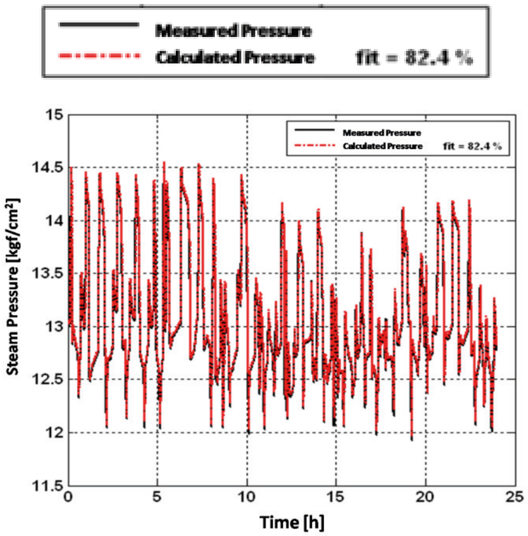

Figure 16. Utilities Sector side pressure fitness

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