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Stochastic method for energy and economic evaluation of cogeneration plants

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Abstract

Cogeneration is one of the processes that allows us to directly face two of the main problems of both industry and society, which are: the generation of greenhouse gases and the high economic uncertainty produced by volatility in the energy market and the complexity of supply chains. Cogeneration allows connecting two or more independent processes, to better take advantage of primary resources, which translates directly into increases in efficiency and reduction of fuel requirements, impacting on the reduction of pollutants and economic uncertainty, unfortunately the high investment costs discourages many entrepreneurs and investors from acquiring this type of technology, that is why a non-deterministic method is required to efficiently limit the variabilities of cogeneration plants.

This study proposes a method, simple but powerful, for the analysis and design of cogeneration systems, which is based on the analysis by Monte Carlo method of the system in its integral form, the proposal was made based on the analysis of operation data of twenty plants installed in the Center and Northwest of the Mexican Republic as well as in the center of the Republic of Panama, the results of the exploratory analysis indicated that ambient temperature, system configuration, price of main equipment, as well as gas and electric power prices are all stochastic variables and that the greatest effect is on gas and electricity price for economics and weather conditions for energetic efficiency.

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I. Introduction

Cogeneration can increase the efficiency with which fuels are used, because it integrates two or more systems energetically, essentially consists of taking advantage of the waste heat of a process to apply it in a different one and in this way minimizes the destruction of exergy. Typical examples of this type of system are combined cycles, electricity, and steam generation, as well as trigeneration or generation of electricity, steam, and refrigeration.

In combined cycles the main objective is the production of electrical energy, so the optimization must be based on maximizing the utility for the energy generated, however, in dual systems (see Figure 1) and in trigeneration systems the utility must be maximized without compromising the needs of heat, steam and cooling; In a certain sense it is restricted optimization, additionally the requirements of these services are not always constant since in many processes they depend on the production stage, presenting seasonal, daily or even hourly variations.

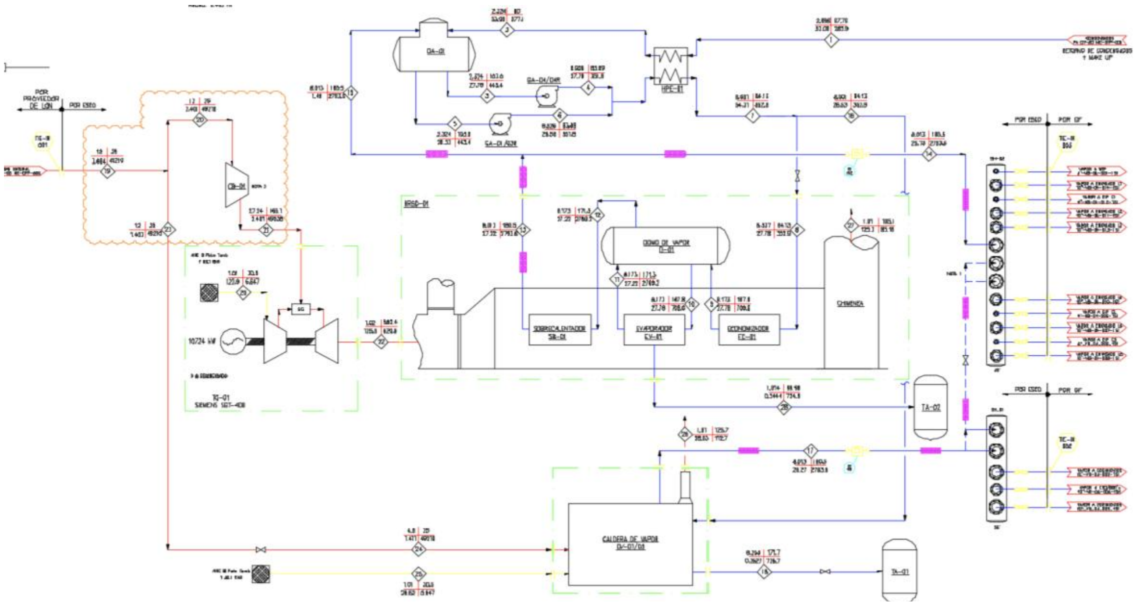


Figure 1 Typical cogeneration system

Despite significantly improving energy efficiency, as high as 60%[1] the use of cogeneration has not spread to expected levels, this is due to the complex dynamics of energy markets [1][2]the sale of electricity surpluses cannot always be guaranteed, as it depends to a large extent on government agencies, who also have the ability to set the prices at which they pay for the energy that the company feeds into the grid.

Therefore, it is imperative to improve thermal efficiency, and not only for economic reasons, but also environmental and even social [2], when energy efficiency and total costs are not adequate for operation, generation or cogeneration projects cannot prosper; this is one of the main reasons why many projects[3] in the aforementioned sector have stopped in the last 5 years[4]as they face economic and/or political problems during any of the phases of the project.

Given that there is uncertainty in political stability as well as a great variation in the prices of fuels and process equipment[5][6], the levelized cost of the energy produced has a high volatility [7][8]however, investors require greater certainty to be able to approve energy projects, before this the application of non-deterministic algorithms provides a probabilistic vision of greater spectrum on the possible scenarios that may arise [9]

These methods, being stochastic in nature, allow social, economic, environmental, and even political phenomena to be considered, producing valuable statistical information instead of point values, which can be analyzed to make informed decisions. Since an increasing number of tools and computing power are available, the application of these methods is faster and more effective.

Proposed Method

The proposed method is based on Montecarlo and combines process simulation with economic evaluation.
Stages comprise data gathering, analysis of uncertainty sources, simulation and finally results analysis, figure 2 shows a schematic of the method.

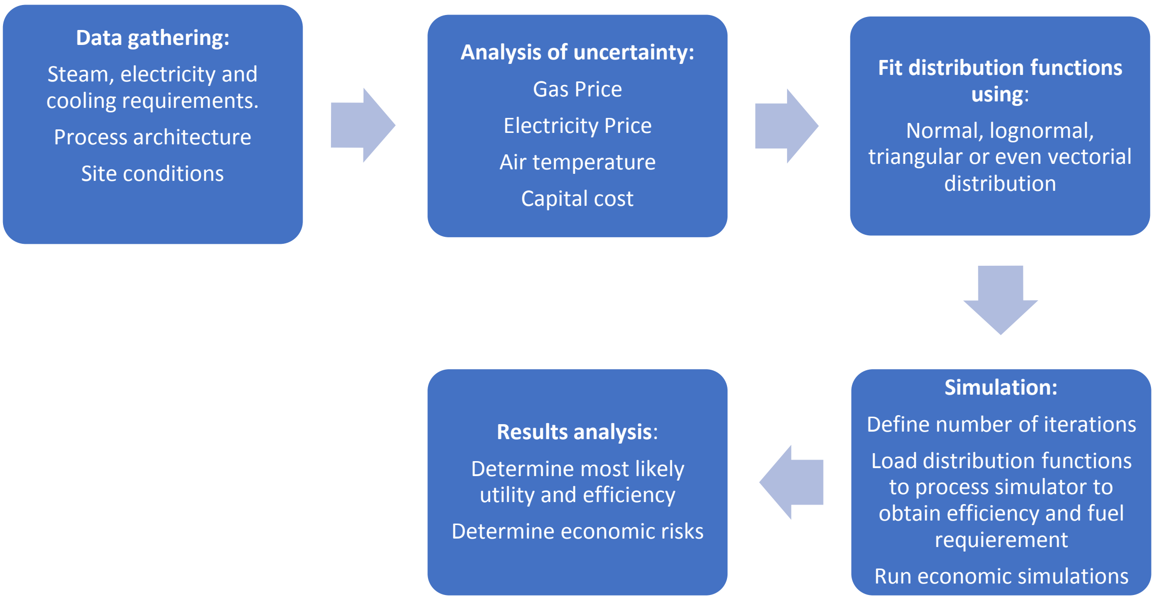


Figure 2Stochastic method for energy and economic evaluation

Data gathering

Probably the most difficult stage is data gathering, in this stage operational data must be defined, including:

- Electric energy requirement
- Steam requirement
- Pressure and temperature levels
- Condensate system
- Source of fresh water
- Type of fuel
- Environmental legislation
- Type of interconnection contract
- System configuration

Figure 3 shows steam requirements for a brewing company, here we can see that steam demand is not constant along a production day.

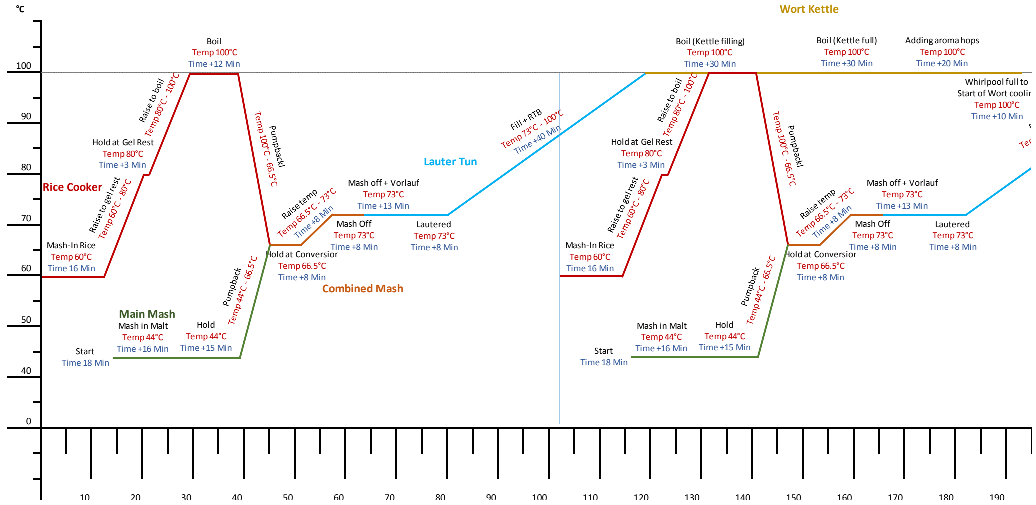


Figure 3Steam requirements for a fictional brewing company

Table 1 presents an example of different system configurations for a new cogeneration plant; final selections is made on an economic basis.

Table 1 Different system configurations for a new cogeneration plant

Scenario	**Configuration**	**Total Steam Production (t/h)**	**Chilledwater Production (6.5 °C, t/h)**
1	Simple Cycle: 1x TG SGT-400 + Boiler 30 t/h	52.0	NA
2	Simple Cycle: 1x TG Mars 100 + Boiler 30 t/h + Absorption Chiller	52.0	64 (452 TR/h)
3	Simple Cycle: 2x TG SGT-400	52.9	NA
4	Simple Cycle: 2x TG SGT-400 + Absorption Chiller	52.0	64 (452 TR/h)
5	Simple Cycle: 1x TG Mars 100 + Boiler 30 t/h	52.0	NA
6	Simple Cycle: 1x TG Titan 130 + Boiler 30 t/h	52.0	NA
7	Simple Cycle: 2x TG Mars 100	46.8	NA
8	Combined Cycle: 1x TG SGT-800+TV	52.0	NA
9	Combined Cycle: 1x TG SGT-800+TV	52.0	NA
10	Boiler 30 t/h + TV	29.1	NA

Analysis of uncertainty sources

A total of 15 cogeneration plants were analyzed, with capacities ranging from 15 to 75MW of electricity, 15 to 60 T/h of steam and 0 to 60 T/h of chilled water, finding that the main sources of variation of the efficiency and economic benefit are: fuel price, electricity price, site temperature and capital cost.

Fuel price: It depends on external factors such as the climate at the production site, political stability, international economic activity, and the decisions of the producing countries. It directly affects the cost of production; the effect of its increase is distributed between steam and electricity depending on the configuration of the plant.

In recent years the variation has not followed a clear trend however an analysis of the density of various time series suggests that it behaves with a lognormal type of distribution, as can be seen in figure 4, this occurs because the distribution is skewed to the right because of sudden price increases due to fortuitous conditions.

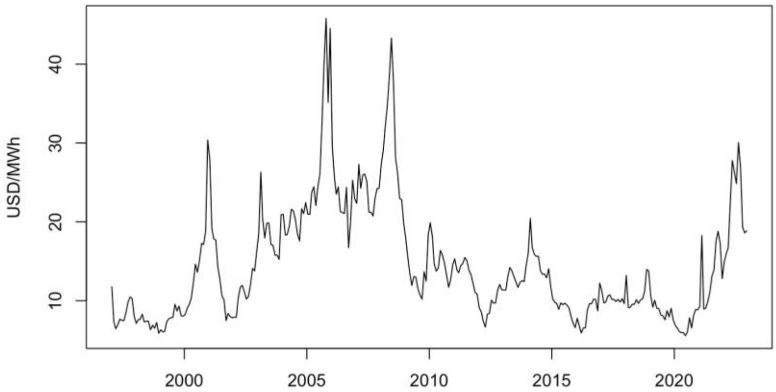


Figure 4Natural gas spot price (Mexico)

Figure 5 shows data for a Mexican cogeneration plant, data must be specific because even inside the same country, gas prices can vary from one region to other.

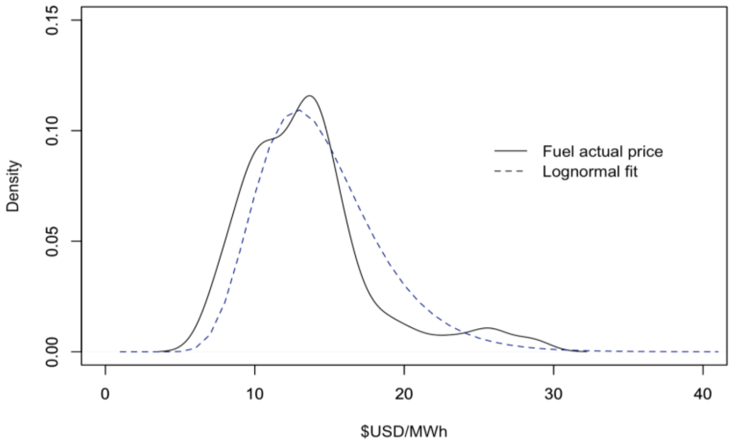


Figure 5Density and lognormal fit of natural gas Price (Mexico)

The best fit for the distribution of natural gas price is described by equation 1, data were fitted using library “fitdistrplus” in RStudio ®.

$$\textbf{Eq. 1} \; \boldsymbol{F(x)} = \frac{1}{2}\left[1 + erf\left(\frac{\ln(x) - 2.5579}{0.2949\sqrt{2}}\right)\right]$$

$$\mu = 2.5579;\ \sigma = 0.2949$$

Electricity sale price: Its variability depends on the site where the cogeneration plant is installed since the sale of electricity is regulated by most governments worldwide. In some countries such as Mexico, plants with generation equal to or greater than 0.5MW must participate in the Wholesale Electricity Market and currently their electricity dispatch is not guaranteed[10].

Figure 6 shows the historical behavior of the sale price of electricity in three representative cities of the United States of America.

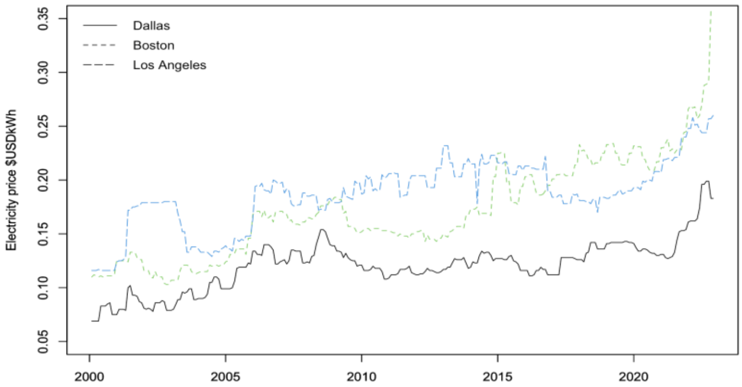


Figure 6Average electricity price for some selected cities of the U.S.

Figure 7 shows the density and normal, lognormal, and triangular adjustments for the data of the city of Los Angeles, observing that the triangular adjustment is the one that best describes the data.

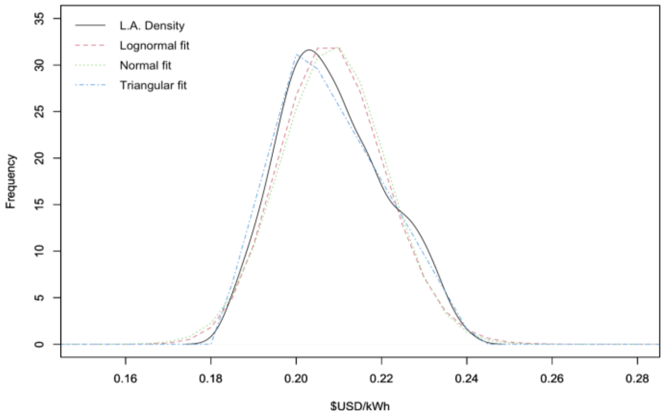


Figure 7 Average electricity price for some selected cities of the U.S.

As can be seen in previous graph, triangular distribution is the one that best fits data. Table 2 shows: minimum, most likely, and maximum parameters for this regression.

Table 2 Parameters for electricity Price triangular distribution

Price type	Value [USD/kWh]
Minimal	0.181
Most likely	0.201
Maximum	0.242

Maximumair temperature: This parameter depends on the installation site of the plant, being essentially a function of geographical factors, although it correlates to a large extent with the solar irradiation received.

The temperature presents a negative effect on efficiency, this occurs because the turbines are volumetric equipment and the higher the temperature of the environment the flow of air entering the system is lower, on the other hand a higher temperature at the entrance of the turbine theoretically requires a smaller amount of gas to reach the same final condition, However, since real equipment is not 100% efficient, this increase also affects performance and polytropic efficiency.

Figure 8 shows the maximum temperatures for the year 2022 in the city of Los Mochis, Sinaloa, Mexico, data were obtained using a Davis Vantage Meteorological station.

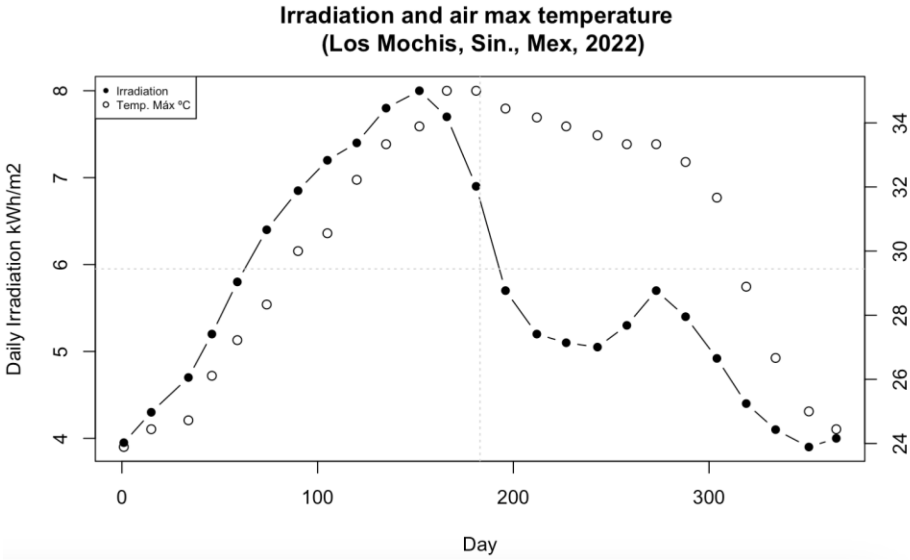


Figure 8Maximum air temperature and irradiation

In this specific case, a density plot does not show a clear trend as we can appreciate in figure 9, so we can define a vector that describes F(x) cumulated frequency and simulate data.

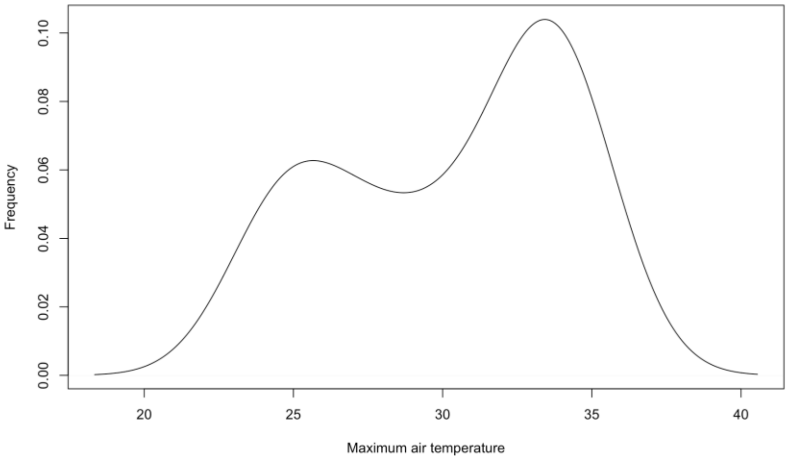
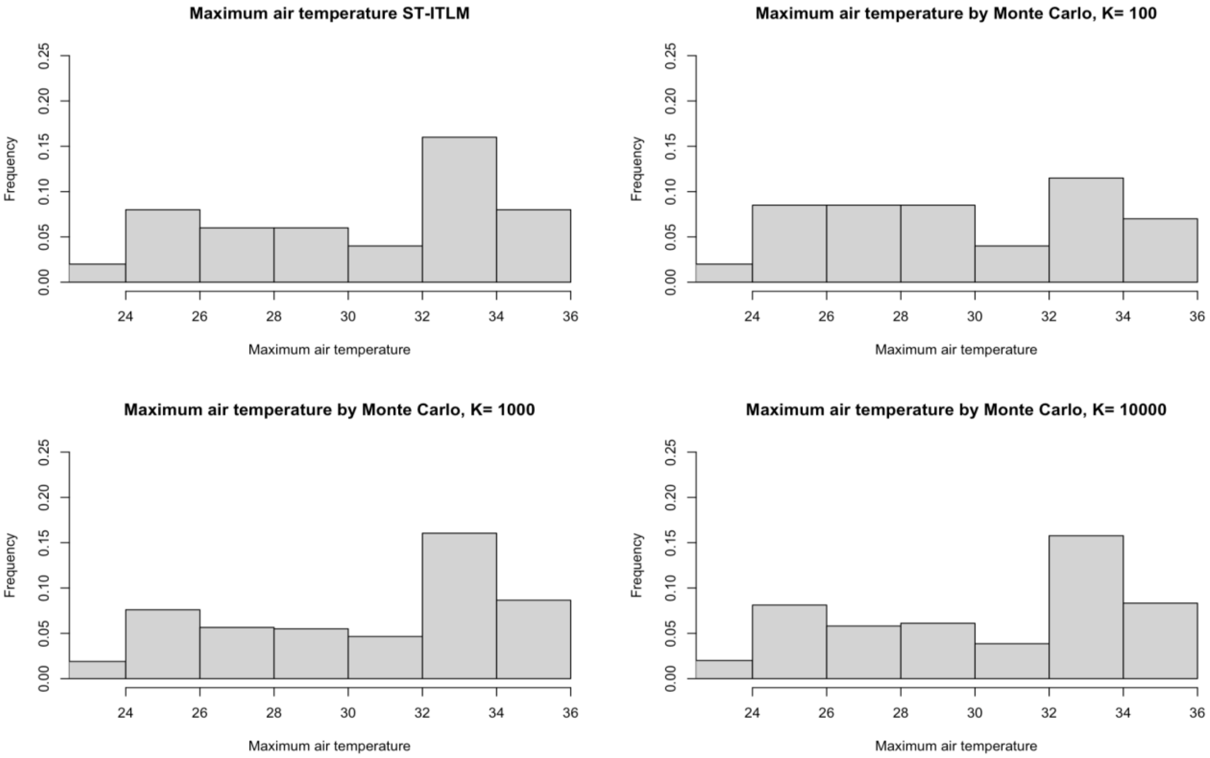


Figure 9 Maximum air temperature density

In figure 10a10,000-run simulation histogram represents very well the real data.


Maximum air temperature ST-ITLM

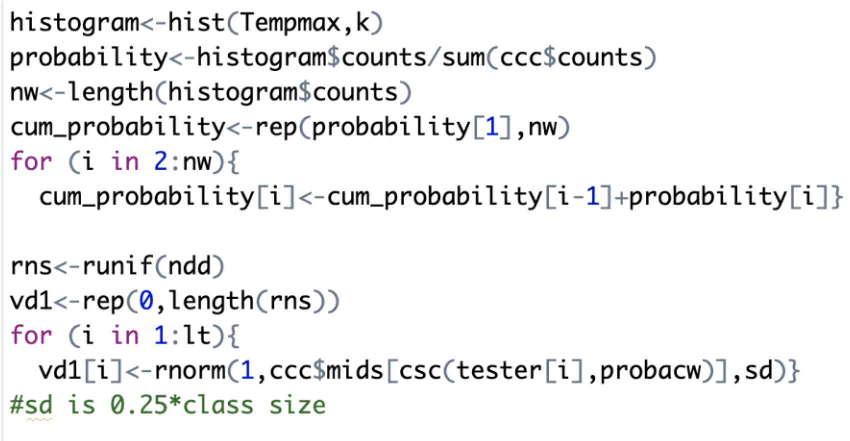
Maximum air temperature by Monte Carlo, K= 100

Maximum air temperature by Monte Carlo, K= 1000

Maximum air temperature by Monte Carlo, K= 10000

Figure 10 Maximum air temperatures for real, 100, 1,000 and 10,000 simulated data

When data don't fit any known distribution, but their behavior is periodical, such as maximum temperature, a cumulated probability vector can be obtained from data; an example of a code to do it, written in RStudio ®, is shown in figure 11.



```
histogram<-hist(Tempmax,k)
probability<-histogram$counts/sum(ccc$counts)
nw<-length(histogram$counts)
cum_probability<-rep(probability[1],nw)
for (i in 2:nw){
  cum_probability[i]<-cum_probability[i-1]+probability[i]}

rns<-runif(ndd)
vd1<-rep(0,length(rns))
for (i in 1:lt){
  vd1[i]<-rnorm(1,ccc$mids[csc(tester[i],probacw)],sd)}
#sd is 0.25*class size
```

Figure 11RStudio code to obtain an F(x) vector

Capital investment: This parameter has a greater variation than the previous ones because it depends on other markets such as steel and electrical materials, so a specific analysis must be carried out in each case.

What is possible to estimate is the investment margin once the price of turbines, heat recuperators and boilers is known since in the cogeneration plants (at least in the 15 analyzed) the costs of construction, pipelines, instrumentation, etc., correlate with those of the main equipment, as can be seen in figure 12 and table 3.

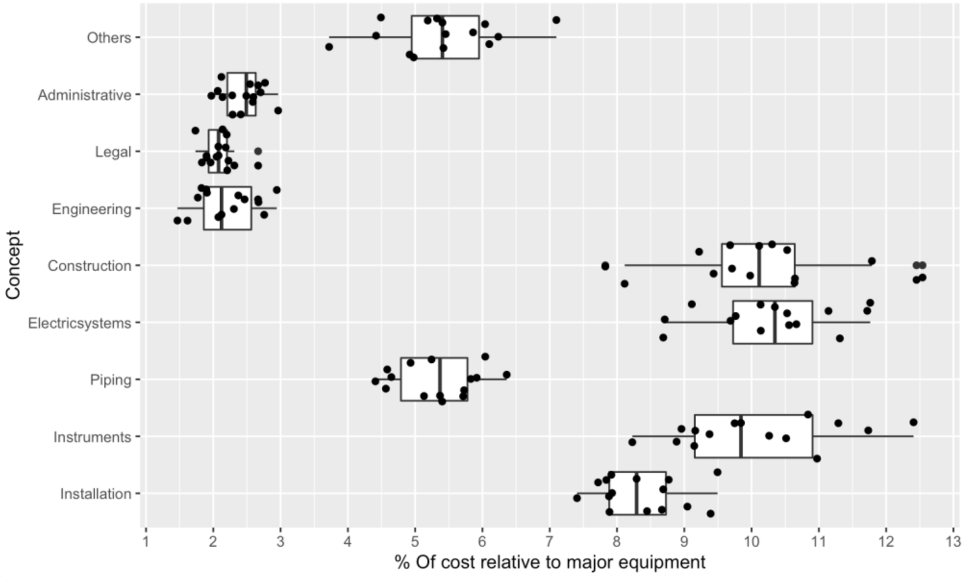


Figure 12Percent of cost relative to major equipment

Table 3 summarizes information about relative costs.

Table 3Percent of cost relative to major equipment

Concept	Mean	Standarddeviation
Installation	8.358	0.634
Instruments	10.091	1.186
Piping	5.325	0.605
Electricsystems	10.284	0.978
Construction	10.198	1.354
Engineering	2.190	0.448
Legal	2.097	0.227
Administrative	2.439	0.289
Others	5.377	0.835

Process simulation

Due to complexity in this kind of systems, the use of a process simulator or computer algorithm is highly recommended, in this paper Aspen Plus ® was used to simulate the cogeneration systems. Figure 13 shows process flowsheet for simulation.

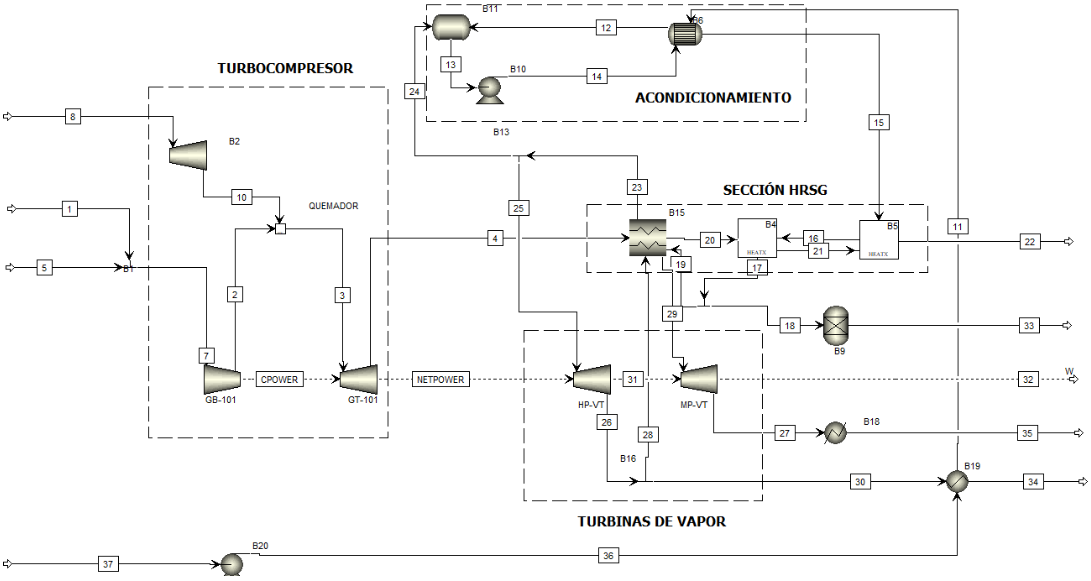


Figure 13Process flowsheet for simulation in Aspen Plus®

The 10 scenarios for system configuration (see table 1), were modeled through the proposed method, using ten million simulations for each case (1e7), for which they were considered:

a) Levelized price of electric power in triangular distribution
b) Levelized price of natural gas in lognormal distribution
c) Energy consumed on site and exported.

The cost of electricity generation in cogeneration is considered as the total cost of operation and maintenance, plus the annualized cost of the investment, plus the cost of human resources minus the cost attributable to the equivalent generation of steam.

All prices, costs and investments are presented in present value in United States dollars of the year 2022, any escalation to current currency must consider the value of inflation.

II. Results

For each of the proposed scenarios, a simulation was carried out with ten million data sets, randomly generated according to the statistical price or temperature distributions, in the Aspen Plus and RStudio software, the data are congruent with the results obtained from plant operation reports.

For the analysis, the plant owner's profit considers the annual savings obtained from the sale of steam, chilledwater, and electricity, as well as the sale of electricity to the grid. Table 4 summarizes annual profit.

Table 4Scenarios overview

Scenario	**Investment**	**Annual Profit Range**			**Return of Investment* [years]**
		Minimum	**More Likely***	**Maxim**	
1	$18,869,775	$1,696,175	$2,335,474	$3,370,290	8.1
2	$19,008,613	$3,231,128	$4,362,521	$6,038,640	4.4
3	**$21,451,781**	**$8,968,161**	**$10,715,970**	**$13,432,162**	**2.0**
4	$21,590,620	$7,890,140	$9,491,564	$12,150,052	2.3
5	$21,451,781	$8,840,514	$10,383,755	$13,099,454	2.1
6	$23,130,620	$8,191,364	$9,903,425	$12,724,636	2.3
7	$35,157,542	$17,160,155	$21,118,292	$27,280,170	1.7
8	$36,697,542	$16,682,489	$20,748,946	$26,978,524	1.8
9	$21,590,620	$7,824,539	$9,298,188	$11,830,429	2.3

10	$24,542,800	$11,407,332	$13,791,544	$17,641,449	1.8

As can be seen in all scenarios, positive utility is generated for the plant owner, for a specific scenario, profit depends on the volatility of the electricity and gas markets.

Figure 14 shows profit distribution for scenario 3, since it is the actual configuration and has been operating for 2 years at an average profit of 10.2 million dollar, which is only 4.7% less than the predicted “most likely value”.

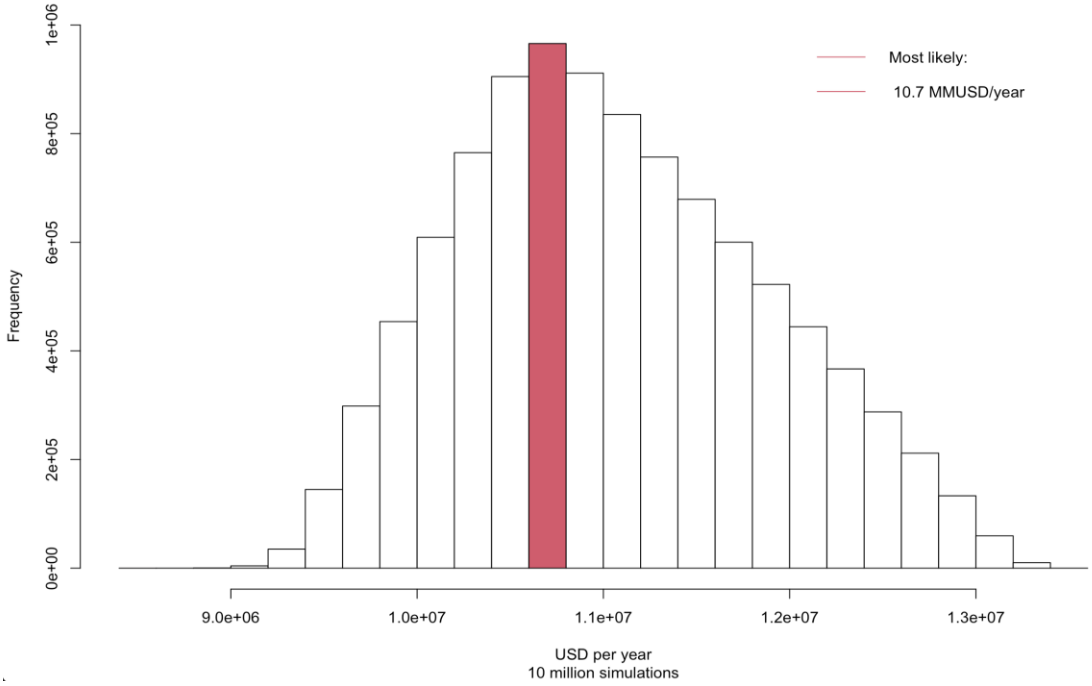


Figure 14Profit stochastic distribution

III. Conclusions

At present, due to high price volatility, it is not possible to perform technical or economic evaluations deterministically, so the use of stochastic evaluation methods is necessary to reduce economic and operational uncertainty.

However, it should not be forgotten, as with any other mathematical model, that the quality of the input information has a direct impact on the quality of the results and that therefore great care must be taken in the choice of the type of probabilistic distribution for each parameter as well as in the calculation of its parameters.

ACKNOWLEDGMENT

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