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HARMONY SEARCH ALGORITHM APPLIED TO WIND ENERGY: DETERMINATION OF WEIBULL CURVE PARAMETERS

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Abstract. *Concern about environmental impacts has accelerated the search for renewable energy sources, which wind energy was highlighted. From then on, the search began for reduce uncertainty values and the wind farms implantation risk. The power estimation values derive from the adjustment parameters of the Weibull curves, which represent the frequency distribution of wind occurrence in the analyzed region. This paper aims to estimate these parameters for the city of Petrolina - PE, Brazil by applying the Harmony Search (HS) algorithm and compare it with the results obtained by deterministic methods. The HS method obtained better results in the analyzed region than the deterministic methods.*

Keywords: *Wind energy, Weibull Distribution, Harmony Search, Heuristic, Deterministic*

1. INTRODUCTION

Since 1970, the renewable energy use has been widely sought. This was due to the oil crises, which led several countries to look for alternatives to reduce dependence on fuel imports and the consequent security of energy supply. Due to environmental concerns, the search for clean energy alternatives has grown. Among these, the wind energy that has attracted significant attention during the last years stands out.

With the objective of enabling the expansion and diversification of the national energy matrix, the Brazilian government established some actions aimed at the sector development, such as the Alternative Energy Sources Incentive Program (PROINFA) creation in 2004. In 2017, a study discussed the different policies and strategies to incentivize investments in renewable energy generation that have been applied in several countries. With focus on the applications, the main advantages and disadvantages of these incentive strategies were emphasized. Some of the strategies applied in Brazil were analyzed in greater detail, emphasizing the potentialities and weaknesses of these mechanisms observed in the country, which, even in relation to other Latin American countries, in relation to the generation of electricity from non-hydro renewable sources still faces barriers that prevent a use compatible with its potential Aquila *et al.* (2017).

Wind resources analysis is a key step in the wind power generation projects development. The reduction of the errors impacts on the forecast of production may, in the worst scenarios, cause financial losses to the investor and, in the underestimation, the wind turbines may be overestimated or overloaded. One of the most important information in the analysis of wind resources is the wind regime characterization according to a distribution of probability Wais (2017).

This paper aims to estimate k e c parameters by the application of Harmony Search, and to compare them with those already obtained by the following deterministic methods: Least Squares Method (LSM), Moment Method (MM), Maximum Likelihood Method (MLM), Energy pattern factor method (EPFM), Modified Maximum Likelihood Method (MMLM), Equivalent Energy Method (EEM), Empirical Method (EM) and Chi-Square Method (χ^2).

2. NUMERICAL METHODS FOR DETERMINING THE WEIBULL PARAMETERS

As the wind speed is a random variable, it is useful to use statistical analysis to determine the wind potential of a region Wais (2017), Celik (2003) and Akpinar and Akpinar (2004). Commonly, the two parameters Weibull distribution is the one that presents the best fit and is therefore the most used to estimate this potential Burton *et al.* (2001) and Manwell *et al.* (2009).

The Weibull distribution for the velocity v is expressed by the probability density function, wind velocity frequency curve, shown in Equation 1. Equation 2 expresses its cumulative probability function Ohunakin *et al.* (2011) and Chang (2011).

$$f(v) = \left(\frac{k}{c}\right) \cdot \left(\frac{v}{c}\right)^{(k-1)} \cdot e^{-\left(\frac{v}{c}\right)^k} \quad (1)$$

$$F(v) = \int_0^v f(v)dv = 1 - e^{-\left(\frac{v}{c}\right)^k} \quad v, k \text{ and } c > 0 \quad (2)$$

Where c is the scaling factor with unit $m \cdot s^{-1}$, k is the shape factor (dimensionless) and $F(v)$ denotes the probability of velocities smaller than or equal to v .

2.1 Maximum Likelihood Method (MLM)

In the Maximum Likelihood Method, numerical iterations are required to determine the Weibull distribution parameters Fisher (1915). In this method Rocha *et al.* (2012), the parameters k and c are determined according to the Equations 3 and 4.

$$k = \left[\frac{\sum_{i=1}^n v_i^k \ln(v_i)}{\sum_{i=1}^n v_i^k} - \frac{\sum_{i=1}^n \ln(v_i)}{n} \right]^{-1} \quad (3)$$

$$c = \left(\frac{1}{n} \sum_{i=1}^n v_i^k \right)^{\frac{1}{k}} \quad (4)$$

Where n is the number of observed data and v_i is the wind speed measured in the interval i .

2.2 Moment Method (MM)

The Moment Method maybe used as an alternative to the Maximum Likelihood Method and it is recommended when the mean and standard deviation of the elements are known and are initially on an appropriate scale Justus *et al.* (1978). In this case Rocha *et al.* (2012), the k and c parameters are determined by the Equations 5 and 6.

$$\sigma = c \cdot \sqrt{\Gamma\left(1 + \frac{2}{k}\right) - \Gamma^2\left(1 + \frac{1}{k}\right)} \quad (5)$$

$$\bar{v} = c \cdot \Gamma\left(1 + \frac{1}{k}\right) \quad (6)$$

Where \bar{v} , σ , Γ are, respectively, the average wind speed, the standard deviation of the observed wind speed data, and the gamma function.

2.3 Empirical Method (EM)

The empirical method Rocha *et al.* (2012) and Chang (2011) is considered a simplified form of the Moment Method, in which the determination of the k parameter follows Equation 7 and the c parameter Equation 8.

$$k = \left(\frac{\sigma}{\bar{v}}\right)^{-1,086} \quad (7)$$

$$\bar{v} = c \cdot \Gamma\left(1 + \frac{1}{k}\right) \quad (8)$$

Where \bar{v} and σ are respectively the mean wind speed and the standard deviation of the observed wind speed data.

2.4 Equivalent Energy Method (EEM)

The Equivalent Energy Method seeks the equivalence between the energy density of the observations and the theoretical Weibull curve. For this, the k parameter is estimated from the third moment of the velocity, by minimizing the square error related to the adjustment, represented by Equation 9 and the c parameter is adjusted by using Equation 10 Silva (2003) and Andrade *et al.* (2014).

$$\epsilon^2 = \sum_{i=1}^n \left\{ W_i - e^{-\left[\frac{(v_i-1)(\Gamma(1+\frac{3}{k}))^{1/3}}{(\bar{v}^3)^{1/3}}\right]^k} + e^{-\left[\frac{(v_i)(\Gamma(1+\frac{3}{k}))^{1/3}}{(\bar{v}^3)^{1/3}}\right]^k} \right\}^2 \quad (9)$$

$$c = \left[\frac{\bar{v}^3}{\Gamma(1 + \frac{3}{k})} \right]^{1/3} \quad (10)$$

2.5 Energy Pattern Factor Method (EPFM)

The energy pattern factor, E_{pf} , method is related to the averaged data of wind speed and is defined by the following equations 11 until 13 Akdag and Dinler (2009):

$$E_{pf} = \frac{\bar{v}^3}{\bar{v}^3} \quad (11)$$

$$k = 1 + \frac{3.69}{(E_{pf})^2} \quad (12)$$

$$\bar{v} = c \cdot \Gamma\left(1 + \frac{1}{k}\right) \quad (13)$$

2.6 Modified Maximum Likelihood Method (MMLM)

The modified maximum likelihood method can only be considered if the available data of wind speed are already in the shape of the Weibull distribution and, as in the maximum likelihood method, it requires numerical iterations for the solution of the equations:

$$k = \left[\frac{\sum_{i=1}^n v_i^k \ln(v_i) f(v_i)}{\sum_{i=1}^n v_i^k f(v_i)} - \frac{\sum_{i=1}^n \ln(v_i) f(v_i)}{f(v \geq 0)} \right]^{-1} \quad (14)$$

$$c = \left(\frac{1}{f(v \geq 0)} \sum_{i=1}^n v_i^k f(v_i) \right)^{\frac{1}{k}} \quad (15)$$

where $f(v_i)$ represents the Weibull frequency and $f(v \geq 0)$ is the probability of wind speed ≥ 0 .

2.7 Least Squares Method (LSM)

The purpose of the method is to define a line where the values of a sample are contained by minimizing the square root of the discrepancy between the value of the sample and the value predicted by the line (objective function) according to Equations 16 until 22 Justus *et al.* (1978):

$$y_i = ax_i + b \quad (16)$$

$$\epsilon_i = y_i - (ax_i + b) \quad (17)$$

$$\epsilon^2 = \sum_{i=1}^n [y_i - (ax_i + b)]^2 \quad (18)$$

$$a = \frac{\sum_{i=1}^n x_i(y_i - \bar{y})}{\sum_{i=1}^n x_i(x_i - \bar{x})} \quad (19)$$

$$b = \bar{y} - a\bar{x} \quad (20)$$

$$k = a \quad (21)$$

$$c = e^{-\frac{b}{k}} = e^{[\bar{x} - (\frac{\bar{y}}{k})]} \quad (22)$$

2.8 Chi-Square Method (χ^2)

Similarly to the adjustment by the equivalent energy method, the Chi-Square method seeks to minimize the error of the Chi-Square test between measured data and the expected data, according to Equations 23 and 24 Dorvlo (2002).

$$\chi^2 = \sum_{i=1}^n \left\{ \frac{[F(v_i) - (1 + \exp(\frac{v_i}{k}))^k]^2}{1 + \exp(\frac{v_i}{k})^k} \right\} \quad (23)$$

$$\bar{v} = c \cdot \Gamma(1 + \frac{1}{k}) \quad (24)$$

It is worth mentioning that for all methods that use frequency distribution values (histogram), the value v_i represents the central value of the speed (*bin*).

3. HEURISTIC METHODS

Heuristics encompasses a set of methods where, to solve a problem, the variables in question use the experience gained over the iterations. Heuristic methods combine different concepts intelligently to explore the search space, so that learning strategies are used to structure information and find efficient and almost optimal solutions Osman and Laporte (1996). Many of the heuristic approaches depend on probabilistic decisions made during the algorithm run. The main difference against pure random search is that in heuristic algorithms randomness is not used blindly but intelligently and biased Stutzle (1999). It is valid to emphasize that every optimization procedure searches for the best result of a function for the desired scenario. This function is called the Objective Function. In this paper, the objective function is the one presented in Equation 25, which represents the minimization of the square error sum applied to the frequency of occurrence values found by the curve adjusted by the method and the observed frequency of occurrence in the histogram of the data.

$$\epsilon^2 = \sum_{i=1}^n (f_{adjustment} - f_{observed})^2 \quad (25)$$

Where n is the number of histogram velocity intervals and $f_{adjustment}$ and $f_{observed}$ are the occurrence frequencies by the adjusted curve and observed in the histogram, respectively.

3.1 Harmony Search (HS)

The Harmony Search is a heuristic algorithm based on the analogy of the artificial phenomenon of a musical group in search of the best harmony. This search occurs through the combination of existing elements and the generation of new elements that are combined to form possible solutions (Geem *et al.*, 2001). The search process begins with the formation of a Harmony Memory (HM), through the memorization of a series of possible solutions, called harmonies. At each iteration a new harmony is formed and compared to the harmonies stored in the HM. The algorithm was presented by the following steps (Askarzadeh and Zebbarjadi, 2014):

1. Initialize the Harmony Memory;
2. Improvise a new harmony from HM;
3. If the new harmony is better than the minimum harmony in HM, include the new harmony in HM and exclude the minimum harmony from HM. If not, the new harmony is excluded;
4. If the stopping criteria are not satisfied, go to step 2.

The algorithm proposed by Mahdavi *et al.* (2007), Geem *et al.* (2001) and Askarzadeh and Zebbarjadi (2014) suggested a method of selecting the harmonic search parameters (HS-NPSA) using the Equations 26 until 28.

$$HCMR = 0,9 + 0,1 \cdot rand(0,1) \quad (26)$$

$$PAR = \frac{1 - rand(0,1)}{2} \quad (27)$$

$$bw = rand(0,1) \quad (28)$$

Where $rand(0,1)$ is the random number in the range of zero to one.

4. METHODOLOGY

The method application and data elaboration applied used the statistical tool called RStudio, integrated development environment of the R language. A wind data series was tested by combining a pair (k, c) , composed by 52,560 speed values, number of values established according to the IEC 61400 PART 12-1(2005) standard that defines 1 (one) year of integrated data every 10 minutes, totaling 52,560 values.

The adjustment tests with real data were performed with public data from the Federal Government's SONDA project, referring to the PTR11 station, located in Petrolina, PE, at 50m at ground level and with one year of data for reasons of availability, the year 2010 was selected and the occurrence of inconsistent data was reviewed.

To analyze the efficiency of the aforementioned methods, the following tests are used: RMSE (Root Mean Square Error), Mean Absolute Error (MAE), R^2 (analysis of variance or efficiency of the method) and the percentage value of the production deviation between the obtained curve and the histogram was also evaluated. These tests are defined by Equation 29 until Equation 32 respectively.

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (y_i^{calculated} - y_i^{measured})^2}{n}} \quad (29)$$

$$MAE = \frac{1}{n} \sum_{i=1}^n |y_i^{calculated} - y_i^{measured}| \quad (30)$$

$$R^2 = \frac{\sum_{i=1}^n (y_i^{measured} - \bar{y}^{measured})^2 - \sum_{i=1}^n (y_i^{measured} - y_i^{calculated})^2}{\sum_{i=1}^n (y_i^{measured} - \bar{y}^{measured})^2} \quad (31)$$

$$WPD = \left(\frac{WPD_{estimated} - WPD_{measured}}{WPD_{measured}} \right) \cdot 100 \quad (32)$$

Where, according to (Jamil *et al.*, 1995), $WPD_{measured}$ and $WPD_{estimated}$ are calculated respectively by Equations 33 and 34

$$WPD_{medido} = \frac{1}{2} \cdot \rho \cdot c^3 \cdot \Gamma \left(1 + \frac{3}{k} \right) \quad (33)$$

$$WPD_{estimado} = \frac{1}{2} \cdot \rho \cdot v^3 \quad (34)$$

Where ρ is the specific mass of the air.

5. RESULTS AND DISCUSSION

Figures 1 present the Weibull distribution curves, described by its probability function $f(v)$, versus wind speed. The HS method was calculated based on the parameters, harmony numbers equal to 8. Figure 1 compares eight deterministic methods and the heuristic method, HS.

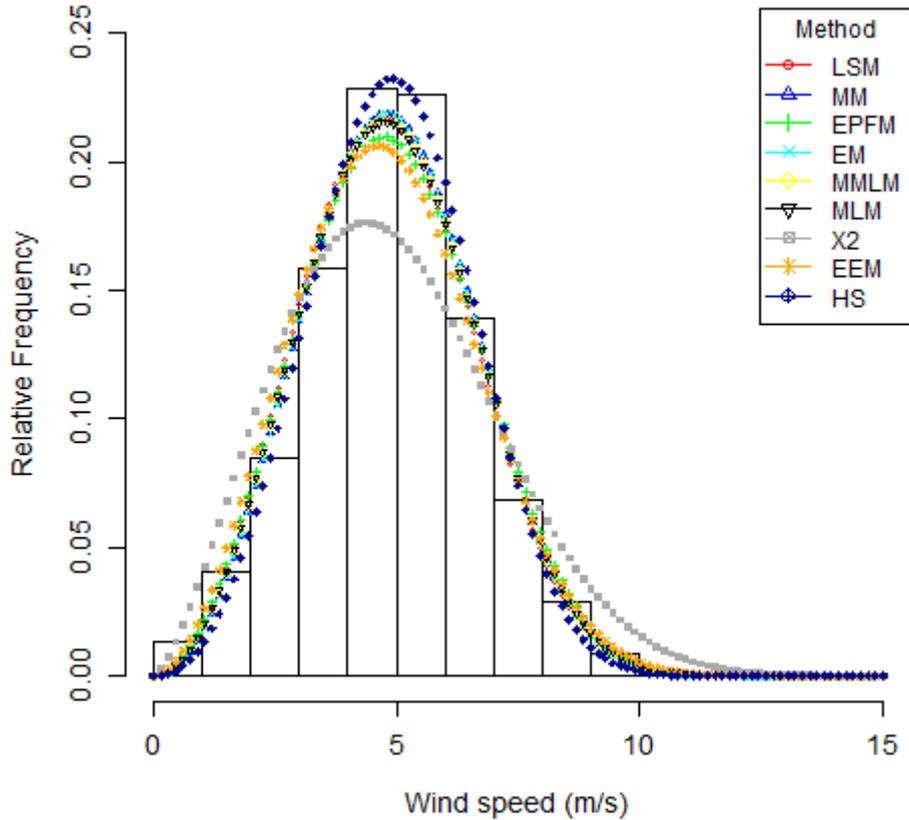


Figure 1. HS and eight deterministic methods Comparison

The results of the statistical tests for the PTR11 station located in Petrolina are presented in Tab.1.

Table 1. Statistical Analysis of Petrolina, year 2010.

Method	k	c	RMSE	MAE	R ²	WPD (%)
LSM	2.9883	5.3996	0.002714	0.006299	0.980309	-2.440258
MM	3.0593	5.4665	0.002282	0.005948	0.986070	0.252696
EPFM	2.9212	5.4776	0.002958	0.007336	0.976597	2.870922
EM	3.0595	5.4665	0.002281	0.005946	0.986081	0.249014
MMLM	3.0258	5.4536	0.002439	0.006081	0.984086	-0.009484
MLM	2.9980	5.4560	0.002569	0.006266	0.982346	0.512640
χ^2	2.3840	5.5121	0.006426	0.016840	0.889589	17.962000
EEM	2.8169	5.3952	0.003639	0.008796	0.964585	$-5.551115 \cdot 10^{-14}$
HS	3.2884	5.4792	0.001727	0.005012	0.992023	-1.683614

According to the Table 1, it can be observed that HS, MM and EM method presented the lowest RMSE test value, 0.001727, 0.002282 and 0.002281, respectively. The heuristic method also presented the best performance when it was analyzed the MAE and R² tests with values of 0.005012 and 0.992023, respectively. The WPD results showed a superiority of the EEM among all methods tested with value of $5.55 \cdot 10^{-14}\%$. HS performed well, since the value obtained, 1.683614%, less than 2%, which was below the acceptable limit for the deviation of Wind Power Density.

The HS method obtained a better fit to the histogram when compared to deterministic methods. It is noticed that the curve suffers a slight shift to the right, in addition, the velocity peak becomes better represented.

6. CONCLUSION

In this paper, eight deterministic and one heuristic optimization methods namely Harmony Search were used to estimate the parameters, k and c , of the Weibull distribution for Petrolina, a city with good conditions, climate and geomorphology, for wind energy generation. The results were compared to each other. The deterministic methods were compared with the HS method, using as a selection criteria the statistical tests. The following conclusions can be drawn based on the results presented in the previous sections:

1. For Petrolina, Equivalent Energy Method stood out, presenting the best performance among all methods tested for the cubic velocity energy production (WPD), obtained the best performance with value of $5.55 \cdot 10^{-14}\%$.
2. Harmony Search Algorithm was an efficient method, for determining the Weibull distribution, k and c parameters, for Petrolina, PE, Brazil.

7. ACKNOWLEDGEMENTS

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