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CUCKOO SEARCH ALGORITHM IN WIND ENERGY APPLICATION FOR A BRAZILIAN SITE

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Abstract. *Wind energy is considered one of the most promising natural sources in the world. A wind farm construction site choice requires a accurate study of it, which includes, as one of the decision parameters, the quality of the wind regime in the region. This study is important because it reduces the building wind farms risk in places with low energy efficiency. The power estimation values derive from the Weibull curves adjustment parameters, scale factor c and shape scale k, which represent the frequency distribution of wind occurrence in the analyzed region. This paper aims to estimate these parameters for São Martinho da Serra city, Rio Grande do Sul, Brazil, by the Cuckoo Search Optimization (CSO) method and compare them with those obtained by deterministic methods. The CSO method obtained better results in the analyzed region than the deterministic methods.*

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

1. INTRODUCTION

Energy, whose demand is constantly increasing, is a very important resource in the development of any nation. The fact that the expansion of the energy matrix has limiting factors, together with the constant search for forms of energy that reduce the emission of carbon dioxide into the atmosphere, has led to the search for energy production methods that have a greater potential for expansion and a smaller aggression degree to the environment. In this context, wind energy presents itself as a proven energy generation with consolidated technology and with great untapped potential.

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).

The wind resource analysis is a fundamental step in the development of wind power generation projects. One of the most important steps in this analysis is the wind regime characterization according to a probability distribution. In this procedure, velocities are grouped in intervals and a probability distribution function is adjusted. Depending on the wind conditions, the curve to be adjusted may follow the Gauss, Rayleigh or, more commonly, Weibull's two parameters distribution Wais (2017). The Weibull distribution can be described as a probability density function $f(v)$ and a cumulative distribution function $F(v)$, determined by Equations 1 and 2 Ohunakin *et al.* (2011) and Chang (2011).

This paper aims to estimate *k* e *c* parameters by the application of Cuckoo Search Optimization, 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).

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

$$F(v) = \int_0^v f(v)\mathrm{d}v = 1 - e^{-(\frac{v}{c})^k} \quad v,\, k\, and\, c > 0 \tag{2}$$

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.

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

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

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.

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

$$\overline{v} = c \cdot \Gamma(1+\frac{1}{k}) \tag{6}$$

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.

$$k = (\frac{\sigma}{\overline{v}})^{-1,086} \tag{7}$$

$$\overline{v} = c \cdot \Gamma(1+\frac{1}{k}) \tag{8}$$

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).

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

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

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):

$$E_{pf} = \frac{\overline{v^3}}{\overline{v}^3} \tag{11}$$

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

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

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:

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

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

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):

$$y_i = ax_i + b \tag{16}$$

$$\epsilon_i = y_i - (ax_i + b) \tag{17}$$

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

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

$$b = \overline{y} - a\overline{x} \tag{20}$$

$$k = a \tag{21}$$

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

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).

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

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

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.

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

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 Cuckoo Search Optimization (CSO)

Cuckoos are birds that present an aggressive breeding strategy. Some species such as Ani and Guira cuckoos place their eggs in communal nests, and may remove others eggs to increase the hatching probability of their own eggs. Other species lay their eggs in nesting host birds (often of other species). New World brood-parasitic Tapera species have evolved in such a way that female parasitic cuckoos are often very specialized in the mimicry in colour and pattern of the eggs of a few chosen host species.This reduces the probability of their eggs to be abandoned and thus increasing their reproductivity Payne *et al.* (2005).

The CSO is derived from the behavior of the cuckoo in the process of finding nests, in which a nest is a possible solution. Initially, an initial population of nests is randomly generated, later new solutions are generated via Lévy flights and from these, the best solutions are stored in comparison to the current solutions. There are several ways to implement the distribution of Lévy, the simplest is the Mantegna′s algorithm Yang (2010), so that the distribution takes the form presented by Equation 26 Jiang *et al.* (2017).

$$x_i^{t+1} = x_i^{(t)} + \alpha_0 \cdot \frac{\phi \cdot u}{|v|^{\frac{1}{\beta}}} \cdot (x_i^{(t)} - x_{best}^{(t)}) \tag{26}$$

Where $X_i^{(t)}$ is the previous solution from which the new solution $X_i^{(t+1)}$ has been generated, $_0$ is a constant, usually 0.01, $X_{best}^{(t)}$ represents the best actual solution, u and v are drawn from normal distributions, β is the scale factor which has an assigned value of 1.5 and ϕ is calculated according to Equation 27, where Γ is the gamma function.

$$\phi = \left\{ \frac{\Gamma(1+\beta) \cdot \sin(\frac{\pi \cdot \beta}{2})}{\Gamma\left[\frac{(1+\beta)}{2}\right] \cdot \beta \cdot 2^{\frac{(\beta-1)}{2}}} \right\}^{\frac{1}{\beta}} \tag{27}$$

Then, the solution subset is discarded according to the probability of detection $P_a \in [0,1]$ and new solutions are obtained, according to Equation 28, with the same quantity of solutions abandoned Jiang *et al.* (2017) and Sanajaoba and Fernandez (2016).

$$x_i^{t+1} = x_i^{(t)} + r \cdot (x_{i,c}^{(t)} - x_{i,k}^{(t)}) \tag{28}$$

In Equation 28, r is an uniformly distributed random number from 0 to 1, and $X_{(i,c)}$ and $X_{(i,k)}$ denote the two random solutions of the ith generation.

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 SMS08 station, located in São Martinho da Serra, RS, 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.

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

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|y_i^{calculated} - y_i^{measured}\right| \tag{30}$$

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

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

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

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

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

Where ρ is the specific mass of the air.

5. RESULTS AND DISCUSSION

Figures 1 present the Weilbull distribution curves, described by its probability function $f(v)$, versus wind speed. The CSO method was calculated based on the parameters, nest numbers equal to 50 and detection probability equal to 0.25. Figure 1 compares eight deterministic methods and the heuristic method, CSO.

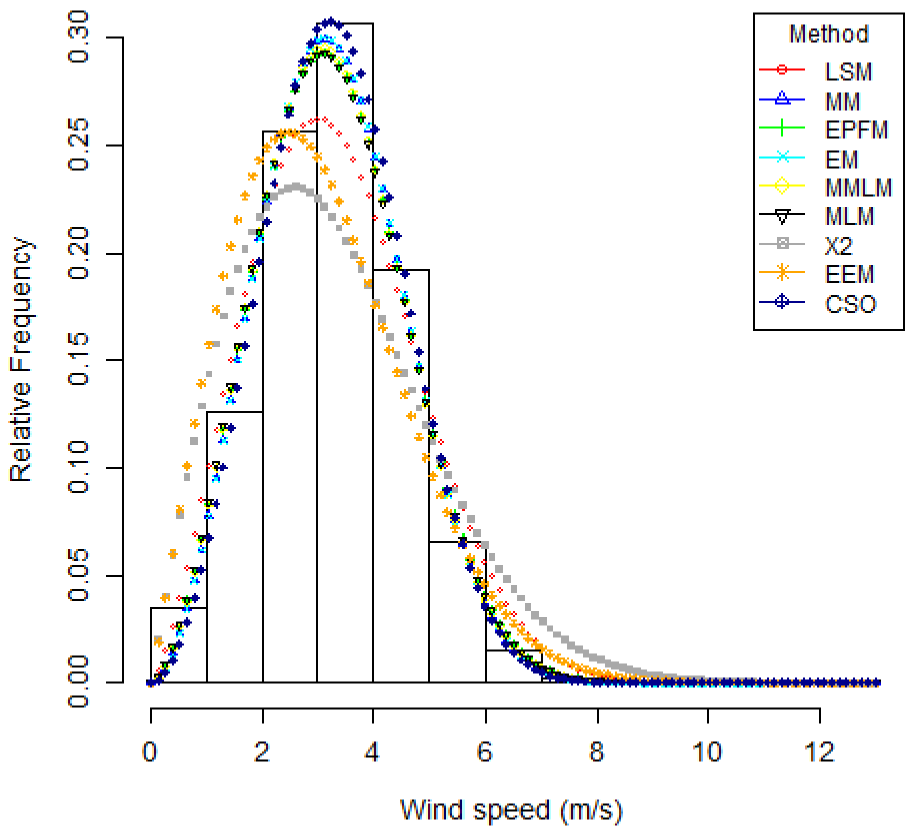

Figure 1. CSO and eight deterministic methods Comparison

The results of the statistical tests for the SMS08 station located in São Martinho da Serra are presented in Tab.1.

Table 1. Statistical Analysis of São Martinho da Serra, year 2010.

Method	k	c	RMSE	MAE	R^2	WPD (%)
LSM	2.4119	3.7395	0.005247	0.011540	0.961880	14.946297
MM	2.7760	3.6717	0.002251	0.005308	0.992982	-0.080201
EPFM	2.7050	3.6751	0.002684	0.006282	0.990020	1.578068
EM	2.7833	3.6713	0.002214	0.005208	0.993208	-0.244181
MMLM	2.7188	3.6600	0.002665	0.006216	0.990160	0.059538
MLM	2.6946	3.6662	0.002799	0.006508	0.989148	1.056167
χ^2	1.9734	3.6870	0.010051	0.024919	0.860125	31.587672
EEM	2.0573	3.4135	0.010163	0.021280	0.856987	$-1.110223 \cdot 10^{-14}$
CSO	2.9102	3.7173	0.001692	0.003700	0.996033	1.347608

According to the Table 1, it can be observed that CSO and EM method presented the lowest RMSE test value, 0.001692 and 0.002214, respectively. The heuristic method also presented the best performance when it was analyzed the MAE and R^2 tests with values of 0.003700 and 0.996033, respectively. The WPD results showed a superiority of the EEM among all methods tested with value of $1.11 \cdot 10^{-14}$%. CSO performed well, since the value obtained, 1.347608%, less than 2%, which was below the acceptable limit for the deviation of Wind Power Density.

The CSO 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 Cuckoo Search Optimization were used to estimate the parameters, k and c, of the Weibull distribution for São Martinho da Serra, 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 CSO 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 São Martinho da Serra, 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 $1.11{\cdot}10^{-14}\%$.

2. Cuckoo Search Optimization was an efficient method, for determining the Weibull distribution, k and c parameters, for São Martinho da Serra, RS, Brazil.

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