17th Brazilian Congress of Thermal Sciences and Engineering
November 25th-28th, 2018, Águas de Lindóia, SP, Brazil

ENCIT-2018-0733
IMPERIALIST COMPETITIVE ALGORITHM APPLIED TO WIND ENERGY FOR A BRAZILIAN SITE AT PARAÍBA

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Abstract. *Due to factors such as the lack of rainfall and the high energy value from thermoelectric plants, Brazil has presented great growth in the electricity generation from wind farms. One of the main points analyzed in the wind farm implementation is the wind regime described by a probability distribution. This paper aims to estimate by heuristic method known as the Imperialist Competitive Algorithm (ICA), the Weibull distribution parameters. The ICA was implemented by the R language for the city of São João do Cariri located in Paraíba state, Brazil, and the results were compared using the statistical tests RMSE, MAE and* R^2*, in addition to the Wind Production Deviation (WPD) value between the curve obtained and the histogram generated from the Wind speed data. The results presented by deterministic methods usually used for this purpose. In spite of the good performance in the statistical tests, the ICA did not prove to be efficient to estimate the weibull parameters curve for the analyzed region, since it obtained WPD equal to 11.86%, higher than the acceptable maximum for the wind production deviation.*

Keywords: *Wind energy, Weibull Distribution, Imperialist Competitive Algorithm, Heuristic, Deterministic*

1. INTRODUCTION

Due to the various problems such as oil shortages, high fuel prices and pollution, countries have begun to adopt more and more renewable and non-polluting energy. the wind energy that has attracted significant attention during the last years stands out.

To reverse the trend of over dependence on fossils fuels, as well as enhance access to cheap and reliable energy, there is need for the country to diversify its energy sources. In addition, new technologies to harness local resources should be embraced to generate energy. This will support economic development and promote self-sufficiency in energy needs with emphasis to the rural poor population Mukulo *et al.* (2014). For global CO_2 emissions reduction to be realised, power generation should strongly depend on utilizing renewable energy systems, especially in the developing countries.

One of the factors that motivate the wind energy application in Brazil is its association with the hydroelectric energy production, since during the dry season the highest wind velocity measurements are recorded and in the rainy season these velocities decrease. Wind energy can not only be applied in order to maintain reservoir levels during the dry season, but also to help production during the rainy season Barbosa (2015)

A effective use of wind energy requires precise wind energy resource assessment. Precise wind speed measurements plays an important role for estimating the wind energy potential of a target site.

This paper aims to estimate k e c parameters by the application of Imperialist Competitive Algorithm, 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 Imperialist Competitive Algorithm (ICA)

The Imperialistic Competitive Algorithm is an algorithm from the Evolutionary Computation field based on the human being sociopolitical evolution. The algorithm begins with N initial countries that are represented by an array of dimension 1 x N_{var}, such that:

$$Countries = (p_1, p_2, p_3, ..., p_{Nvar})$$

Where N_{var} is the number of variables in the problem.

The best countries, with minimal cost, are chosen as imperialists. The country cost is given by the calculation of the Objective Function through its variables.

$$Cost = f(countries) = (p_1, p_2, p_3, ..., p_{Nvar})$$

The remaining countries are colonies belonging to the imperialists. The algorithm starts when the populationÂt's size N_{pop} is generated. N_{imp} represents the most powerful countries that will form an empire. N_{col} represents the population of colonies that will belong to each empire. The colonies will be distributed among the imperialists according to their respective powers. For this, a normalized cost is defined according to equation 26:

$$C_n = c_n - max_i(c_i) \tag{26}$$

Where c_n is the cost of the nth imperialist and C_n is the normalized cost. From normalized cost the normalized power p_n of an imperialist is defined by equation 27.

$$p_n = \frac{|C_n|}{|\sum_{i=1}^{N_{imp}} c_i|} \tag{27}$$

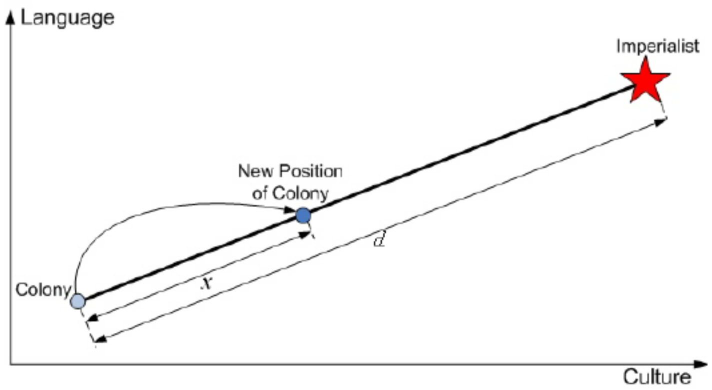
The imperialist normalized power represents the amount of initial colonies that will be assigned to it, given by equation 28.

$$N \cdot C_n = round(p_n \cdot N_{col}) \tag{28}$$

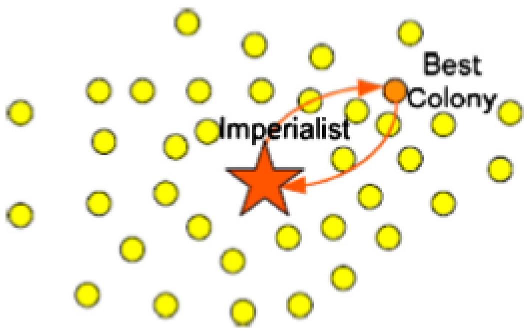
Where $N \cdot C_n$ is the initial number of colonies that the i-th imperialist will possess and the rounding operation assigns a nearest integer value. The empires are formed from an imperialist with their respective colonies. The algorithm main operation of search for new solutions is the colonies movement in relation to the imperialists and The assimilation policy shown in Figure 1 (a), because at each iteration all the colonies move toward their respective imperialists. This movement is governed by two algorithm parameters: the assimilation coefficient (γ) and the angular coefficient of assimilation (δ). Equation 29 describes the movement. Figure 1 (b) is the core of this algorithm and causes countries to move to a minimum.

$$pos_{i+1} = pos_i + \delta \cdot \gamma \cdot d \tag{29}$$

Where pos_i is the colony positioning vector, $\gamma > 1$, δ is a value between 0 and 1 and d is the distance between the colony and its imperialist. The assimilation policy shown in Figure 1 is the core of this algorithm and causes countries to move to a minimum.



(a) Assimilation policy



(b) The colony and imperialist displacement

Figure 1. Weibull curve (a) Generic image of colony movement toward imperialist using assimilation policy (b) The colony and imperialist displacement

The total cost of an empire, Equation 30, is given by the imperialist cost plus a part of the total cost of its colonies.

$$T \cdot C_n = Cost(imperialist) + \varepsilon \cdot mean\{cost(colonies\ of\ empire)\} \tag{30}$$

Where $T \cdot C_n$ is the total cost of the empire and Îţ is a value between 0 and 1. Through revolution it is still possible for a colony to shift to a new position that is randomly generated. The probability of this happening is due to an adjustable parameter called the rate of revolution, T_{rev}, which indicates that the socio-political characteristics of a country change. The imperialist competition happens when the weaker colony of the weaker empire may be conquered by another empire with greater chance of acquiring it. In this case, the normalized cost of empires is defined according to Equation 31.

$$N \cdot T \cdot C_n = T \cdot C_n - max_i(T \cdot C_i) \tag{31}$$

Where $N \cdot T \cdot C_n$ is the normalized cost of the nth empire and $max_i(T \cdot C_i)$ is the total cost of the empire with the highest total cost of all. Having the normalized total cost, the possession probability of each empire is given by Equation 32.

$$P_{pn} = \frac{|N \cdot T \cdot C_n|}{|\sum_{i=1}^{N_{imp}} N \cdot T \cdot C_i|} \tag{32}$$

The vector **P** is defined as the possession probabilities of each empire and the vector **R**, the same size as **P**, with random numbers evenly distributed between 0 and 1, such that:

$$P=(p_{p1}, p_{p2}, p_{p3}, ..., p_{Nimp})$$

$$R=(r_1, r_2, r_3, ..., r_n)$$

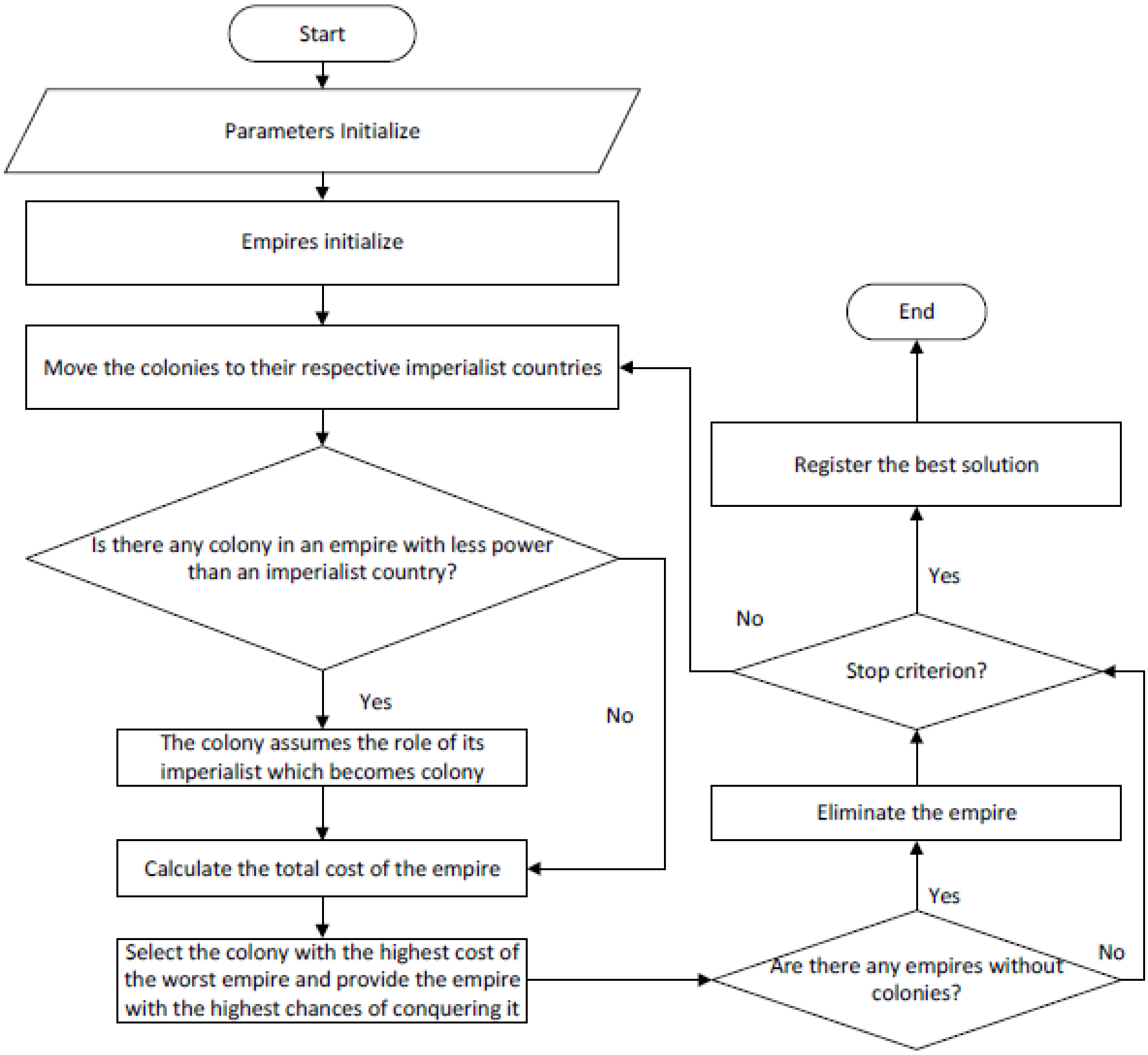
Then we form vector **D** by simply subtracting **R** from **P**:

$$D=P-R=(D_1, D_2, D_3, ..., D_{Nimp})$$

The empire that has the greatest value index of **D** will own the colony. Therefore, the algorithm will analyze whether there are any empires without colonies and, if any, the empire will be eliminated. After reaching a certain number of iteractions, all empires will be extinct, except the most powerful, which will have all the colonies under its dominion and all the colonies will be in the same position and same cost as the one of the imperialist, finalizing the algorithm E. and Lucas (2007) Moradi *et al.* (2014).

Figure 2 shows the flowchart of the proposed algorithm, summarizing all steps described previously.

Figure 2. Flowchart of the proposed algorithm



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 SCR25 station, located in São João do Cariri, PB, at 50m at ground level and with one year of data for reasons of availability, the year 2006 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 33 until Equation 38 respectively.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i^{calculated} - y_i^{measured})^2}{n}} \tag{33}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|y_i^{calculated} - y_i^{measured}\right| \tag{34}$$

$$R^2 = \frac{\sum_{i=1}^{n}(y_i^{measured} - \bar{y}^{measured})^2 - \sum_{i=1}^{n}(y_i^{measured} - y_i^{calculated})^2}{\sum_{i=1}^{n}(y_i^{measured} - \bar{y}^{measured})^2} \tag{35}$$

$$WPD = \left(\frac{WPD_{estimated} - WPD_{measured}}{WPD_{measured}}\right)\cdot 100 \tag{36}$$

Where, according to (Jamil *et al.*, 1995), $\text{WPD}_{measured}$ and $\text{WPD}_{estimated}$ are calculated respectively by Equations 37 and 38

$$WPD_{medido} = \frac{1}{2}\cdot\rho\cdot c^3\cdot\Gamma\left(1+\frac{3}{k}\right) \tag{37}$$

$$WPD_{estimado} = \frac{1}{2}\cdot\rho\cdot v^3 \tag{38}$$

Where ρ is the specific mass of the air.

5. RESULTS AND DISCUSSION

Figures 3 present the Weilbull distribution curves, described by its probability function $f(v)$, versus wind speed. The ICA method was calculated based on the parameters, countries numbers equal to 26, imperialist number equal to 3 and revolution rate equal to 0.3. Figure 3 compares eight deterministic methods and the heuristic method, ICA.

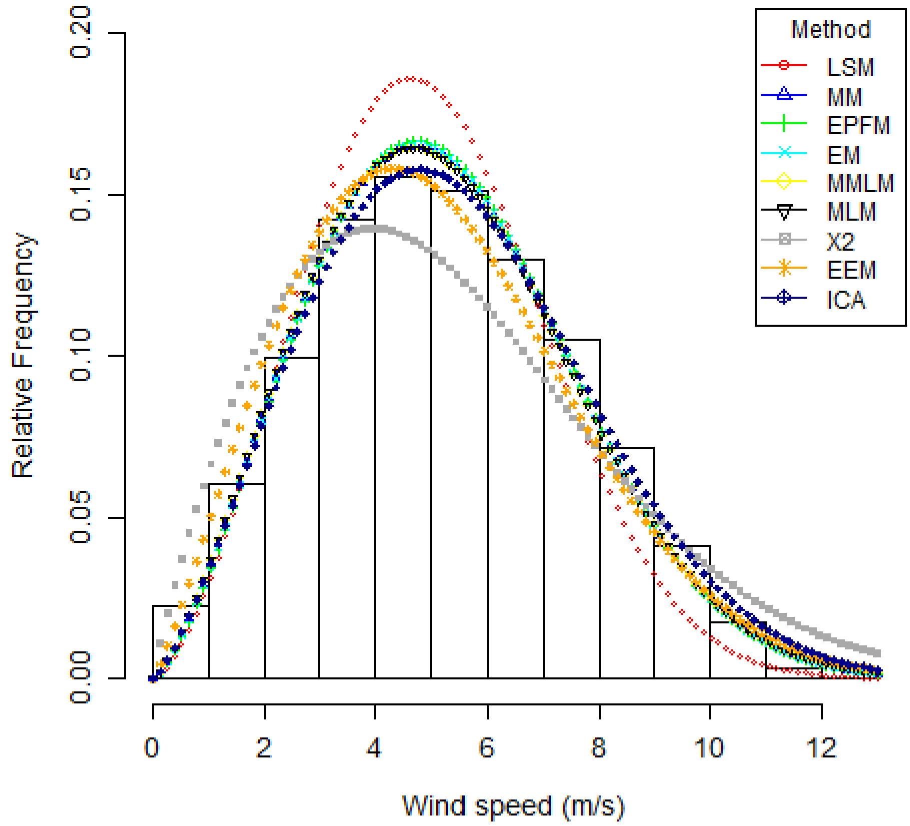


Figure 3. ICA and eight deterministic methods Comparison

The results of the statistical tests for the SCR25 station located in São João do Cariri are presented in Tab.1.

Table 1. Statistical Analysis of São João do Cariri, year 2006.

Method	k	c	RMSE	MAE	R^2	WPD (%)
LSM	2.5944	5.5884	0.004359	0.013233	0.905541	-18.834529
MM	2.3918	5.9096	0.001649	0.005211	0.986474	1.265495
EPFM	2.4230	5.9081	0.001767	0.005701	0.984480	0.262710
EM	2.4081	5.9088	0.001706	0.005466	0.985529	0.737484
MMLM	2.3719	5.8935	0.001673	0.005109	0.986091	1.055361
MLM	2.3709	5.8930	0.001673	0.005102	0.986085	1.060396
χ^2	1.8791	5.9012	0.004650	0.0148259	0.892530	26.587310
EEM	2.1687	5.7325	0.002853	0.008311	0.959552	$-4.440892 \cdot 10^{-14}$
ICA	2.3380	6.0747	0.001141	0.003437	0.993522	11.857580

According to the Table 1, it can be observed that ICA method presented the lowest RMSE test value, 0.001141. The heuristic method also presented the best performance when it was analyzed the MAE and R^2 tests with values of 0.003437 and 0.993522, respectively. The WPD results showed a superiority of the EEM among all methods tested with value of $4.44 \cdot 10^{-14}$%. ICA did not performed well, since the value obtained, 11.8575%, more than 2%, which was below the acceptable limit for the deviation of Wind Power Density.

The ICA 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 Imperialist Competitive Algorithm were used to estimate the parameters, k and c, of the Weibull distribution for São João do Cariri, 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 ICA 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 João do Cariri, 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 $4.44{\cdot}10^{-14}\%$.
2. ICA obtained better performance than Deterministic methods in the statistical tests RMSE, MAE and R^2 with errors in the third decimal place.
3. Imperialist Competitive Algorithm was not an efficient method for determining the Weibull distribution, k and c parameters, for São João do Cariri, PB, Brazil, because WPD value is equal to 11.8%, exceeding the acceptable maximum for the wind production deviation.

7. ACKNOWLEDGEMENTS

This research was jointly supported by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Brazilian governmental agencies.

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