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Analysis of the wind average speed in different Brazilian states using the nested GR & R measurement system

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ABSTRACT

Brazil presents remarkable potential for wind power generation. This study aims to evaluate the behavior of wind average speed at the four major wind energy-producing states. The main contribution of this research is to use the NGR & R study (Nested Gage Repeatability & Reproducibility), generally applied on manufacturing quality management. Wind average speeds were collected for each month in four states, between the years of 2012 and 2015. Seasonality impact, measurements recurrence over the years and difference between states on wind average speed were assessed in this research. Time series, boxplot and control charts have been used to investigate not only wind average speed between months and states, but also range variation for each state by month. Study results show that the impact of these three factors is statistically significant and that the different location of these states presents the most relevant impact to wind mean speed variation in the country.

1. Introduction

Renewable Energy Sources (RES) are able to reduce both greenhouse effect gases emissions and dependence of society on fossil fuels for power generation [1,2]. In this aspect, wind energy is one of the low carbon dioxide (CO_2) emitting RES, although the technology related costs to exploit this source are superior in comparison to conventional sources [3,4].

Therefore, government entities from several countries have issued policies in order to attract investors financially to power generation, especially electric power, through RES, such as wind power [5–7]. Past the energy crisis on 2001 and 2002, Brazil was one of the countries to adopt incentive policies for the renewable energy market. The country launched the Program of Incentives for Alternative Electricity Sources (PROINFA), intended to assign 3300 MW of electric power, produced by wind power, small hydroelectric power plants and biomass [8].

Approximately 1422.92 MW of wind power were assigned with PROINFA [8–10] and, since then, this power source has exponentially grown in the Brazilian electric power matrix. From 2009 onwards, wind power generation projects have gradually started to be assigned through auctions and, afterwards, free market as well, so that prices have become lower than on PROINFA and productive capacity have increased yearly [11].

According to the Brazilian Wind Power Potential Map, issued by CEPEL [12], and to Pereira Junior et al. [9], the country presents higher wind power generation potential in the Northeast and South regions, and the average capacity factor of wind farms in Brazil is 38.1%, performance superior to several countries [13]. In addition, presently there are wind farms in eleven Brazilian states, and these are the states where productive capacities are higher: Rio Grande do Norte (RN) (3408.1 MW), Bahia (BA) (1897.8 MW), Ceara (CE) (1759.1 MW) and Rio Grande do Sul (RS) (1644.4 MW) [14].

A determining factor for wind power generation is the wind speed intensity on areas where wind turbines are installed. Because in Brazil the territory is extensive and wind power generation potential is present on regions with diverse weather conditions, the hypothesis of occurrence of different intensities on wind formation in these locations can be argued. Moreover, there is the possibility of seasonality differences at each month and from one year to another.

Hence, the present study aims to identify whether statistically significant differences exist among the wind average speed of the four major states on wind energy productive capacity. Furthermore, it aims

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to verify whether there is also a difference among the wind average speed in each state from 2012 to 2015. The performance of the Nested Gage Repeatability e Reproducibility (NGR & R) measurement system analysis is an innovation proposed by this study, to use a measurement system commonly adopted by the manufacturing industry in the behavioral analysis of wind average speed in several Brazilian locations.

According to Burdick et al. [15] and Pereira et al. [16], Gage Repeatability and Reproducibility (GR & R) is a particular study of measurement system analysis employed to determine whether the variability of the measurement system is relatively less than the variability of the monitored process. In this aspect, repeatability is the variation of common or internal cause represented by multiple measurements of an operator, using a certain instrument, which evaluates a quality characteristic of an object. Reproducibility, in turn, is the variation between or special cause related to the average of distinct operators on the measurement of a quality characteristic of an object [17,18]. Several graphs can be used to identify significant sources of measurement error. In NGR & R studies, the main effects plot of the operator factor is used to evaluate the reproducibility error and the R control chart to evaluate the repeatability error. Examples applying these graphs to evaluate repeatability and reproducibility errors can be seen at [19–21].

2. Materials and methods

Measurement system capability, through GR & R, is an important study of quality improvement efforts [15]. By the use of GR & R, it is possible to estimate the amount of variation resulting from the measuring gauge and evaluate its adequacy for a specific application. According to Wang and Chien [22], there are two methods commonly used for GR & R analysis: the variance analysis (ANOVA) and the Xbar and R graphics. Yet, the authors emphasize that ANOVA is the favorite method among analysts, because it is able to quantify the measurement error considering interaction between the part and the operator, more details on the ANOVA method can be found on Wang and Chien [22].

Based on GR & R studies, it is possible to estimate how much of the variation is due to the measuring gauge and evaluate whether the measurement system is adequate for a given application [16,23]. In GR & R studies, when the levels of one factor are similar but not exactly the same levels of the other factor, the arrangement is called nested design [24,25]. In such arrangement, there is no interaction term between the two factors and the ANOVA model can be written as follows [15,26]:

$$Y_{ijk} = \mu_Y + \beta_j + \alpha(\beta)_{i(j)} + \varepsilon_{ijk} \begin{cases} i = 1,\dots,p \\ j = 1,\dots,o \\ k = 1,\dots,r \end{cases} \tag{1}$$

where Y_{ijk} is the variable of measured response; μ_Y is the average of measured values; $\beta_j \sim N(0, \sigma_\beta)$; $\alpha(\beta)_{i(j)} \sim N(0, \sigma_{\alpha(\beta)})$ and $\varepsilon_{ijk} \sim N(0, \sigma_\varepsilon)$ are random and independent variables in relation to operators, parts nested within operators and the error term, respectively; p, o and r are the numbers of parts, operators and replicates, respectively.

The variance components in Eq. (1) can be translated into NGR & R notation, as observed in the following [15]:

$$\sigma^2_{process} = \sigma^2_{\alpha(\beta)} \tag{2}$$

$$\sigma^2_{repeatability} = \sigma^2_\varepsilon \tag{3}$$

$$\sigma^2_{reproducibility} = \sigma^2_\beta \tag{4}$$

$$\sigma^2_{NGR\&R} = \sigma^2_{repeatability} + \sigma^2_{reproducibility} \tag{5}$$

$$\sigma^2_{total} = \sigma^2_{process} + \sigma^2_{NGR\&R} \tag{6}$$

Aforementioned variance components can be estimated by using the equations below:

$$\sigma^2_\varepsilon = MS_\varepsilon \tag{7}$$

$$\sigma^2_\beta = \frac{MS_\beta - MS_{\alpha(\beta)}}{pr} \tag{8}$$

$$\sigma^2_{\alpha(\beta)} = \frac{MS_{\alpha(\beta)} - MS_\varepsilon}{r} \tag{9}$$

The mean squares for operators, parts within operators and the error term can be estimated by the nested ANOVA in Table 1. Variables in this Table are described as such: x_{ijk} is each observation; $\overline{x}_{ij.}$ is the mean for part i, within operator j; $\overline{x}_{.j.}$ is the mean of each operator j and; $\overline{x}_{...}$ is the grand mean.

Basically, the nested ANOVA distinguishes from a crossed ANOVA when estimating GR & R components of variation in Eqs. (1)–(4), the mean squares in Eqs. (7)–(9), and the sum of squares related to process variation. More details on nested and crossed designs in GR & R studies, see Burdick et al. [27].

After variance calculation by means of nested ANOVA, in order to evaluate if the measurement system is acceptable or not, the ratio calculation between the NGR & R standard deviation and total standard deviation must be performed [18]. Eq. (10) represents the calculation utilized to evaluate the measurement system:

$$\%NGR\ \&\ R = \left(\frac{\sigma_{NGR\&R}}{\sigma_{total}}\right) \times 100\% \tag{10}$$

It is worth mentioning that in order to obtain the contribution percentage in relation to the other variation components, the numerator of Eq. (10) must be changed.

If the index demonstrates a result below 10%, the measurement system is considered acceptable, if the result lies within 10% and 30%, the measurement system is considered marginal (depending on the application it is acceptable), and for results above 30%, the measurement system is considered unacceptable [16,28,29].

Another metric utilized to evaluate the measurement system is the signal to noise ratio or number of distinct categories (ndc) which is presented by Eq. (11). A value greater than five is expected; a value less than two indicates that the measuring system is not effective to monitor the process [15,28,29].

$$ndc = \sqrt{\frac{2\sigma^2_{process}}{\sigma^2_{NGR\&R}}} = \sqrt{2}\,\frac{\sigma_{process}}{\sigma_{NGR\&R}} \tag{11}$$

Table 1
Analysis of variance table for the nested design.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F-values	P-values
Operator	$SS_\beta = pr\sum(\overline{x}_{.j.} - \overline{x}_{...})^2$	$o-1$	$MS_\beta = \frac{SS_\beta}{DF_\beta}$	$\frac{MS_\beta}{MS_{\alpha(\beta)}}$	$F_0 > F_{0.05,o-1,o(p-1)}$
Part (Operator)	$SS_{\alpha(\beta)} = r\sum\sum(\overline{x}_{ij.} - \overline{x}_{.j.})^2$	$o(p-1)$	$MS_{\alpha(\beta)} = \frac{SS_{\alpha(\beta)}}{DF_{\alpha(\beta)}}$	$\frac{MS_{\alpha(\beta)}}{MS_\varepsilon}$	$F_0 > F_{0.05,o(p-1),op(r-1)}$
Repeatability	$SS_\varepsilon = \sum\sum\sum(x_{ijk} - \overline{x}_{ij.})^2$	$op(r-1)$	$MS_\varepsilon = \frac{SS_\varepsilon}{DF_\varepsilon}$		
Total	$SS_{Total} = \sum\sum\sum(x_{ijk} - \overline{x}_{...})^2$	$opr-1$			

Table 2
Monthly wind mean speed (m/s) measurements by states.

State (Operators)	Year (Replicates)	Month (Parts)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
BA	2012	8.80	11.50	8.50	8.39	9.31	9.17	9.17	11.06	10.18	10.02	5.89	7.81
	2013	6.99	9.40	7.80	7.85	8.26	9.24	9.64	10.28	10.22	9.50	8.42	5.62
	2014	9.34	9.29	8.38	7.43	8.35	9.40	10.18	9.59	9.64	9.76	7.88	7.74
	2015	8.76	8.11	7.63	7.24	8.89	9.87	9.71	9.90	9.37	9.70	7.78	8.43
CE	2012	8.71	7.27	6.93	7.01	8.08	7.88	8.90	9.70	9.86	10.44	9.11	9.21
	2013	8.24	8.69	8.10	6.05	7.43	7.63	8.03	9.63	10.44	10.55	10.04	9.42
	2014	8.55	7.81	7.00	5.89	5.88	7.84	8.50	9.63	10.07	10.30	9.41	9.45
	2015	8.92	7.68	6.40	6.17	7.80	7.86	8.50	9.75	10.11	10.09	9.16	8.98
RN	2012	8.30	8.10	8.27	8.43	8.60	8.62	9.10	10.45	9.51	9.72	8.41	8.52
	2013	8.23	8.74	7.97	7.00	7.96	7.69	8.35	9.53	9.35	9.17	8.97	8.22
	2014	8.60	8.01	7.44	6.83	7.19	7.54	8.97	9.83	9.13	9.58	8.40	8.29
	2015	8.40	7.57	7.01	6.60	7.98	7.95	8.39	9.80	9.10	9.14	8.20	8.10
RS	2012	7.28	6.01	6.35	6.61	6.41	6.08	6.62	8.10	8.63	8.43	7.96	7.33
	2013	7.05	6.84	6.88	6.95	5.93	6.20	6.32	7.26	7.40	7.79	9.06	7.81
	2014	6.78	7.56	6.99	7.32	5.84	7.82	7.69	7.33	8.24	8.17	7.73	7.03
	2015	6.64	6.67	6.74	6.40	6.64	6.30	6.27	7.95	7.30	8.35	7.89	7.09

Whenever the measurement system is deemed either marginal or unacceptable, some graphics can be used to identify the source of measurement system variation. The R chart can be used to check whether the measurement process is in control with respect to repeatability [29]. Considering that $y_1, y_2, \ldots, y_n$ is a sample of size n, then the range of the sample is calculated as follows:

$$R = y_{\max} - y_{\min} \tag{12}$$

Let $R_1, R_2, \ldots, R_m$, be the ranges of the m samples. The average range is:

$$\overline{R} = \frac{R_1 + R_2 + \cdots + R_m}{m} \tag{13}$$

Repeatability may be monitored by plotting values of the sample range R on a control chart. The center line and control limits of the R chart are obtained by [30]:

$$\begin{aligned} UCL &= \overline{R} + 3\overline{R}\frac{d_3}{d_2} \\ Center\ Line &= \overline{R} \\ LCL &= \overline{R} - 3\overline{R}\frac{d_3}{d_2} \end{aligned} \tag{14}$$

where d_3 and d_2 are constants used to estimate the standard deviation of R chart. For more information on these constants, see [30].

However, it is important to stress that, differently from analysis performed on manufacturing processes, for the application performed on this study the evaluation of whether the measurement system is acceptable or not is not the most important factor. An eventual acceptance of NGR & R will indicate that there is no significant difference between wind average speeds over the years and between the analyzed states, therefore acceptance would indicate that there is only the difference resulting from seasonality.

Typically, in NGR & R studies, $p \geq 10$ parts, $o \geq 3$ operators and $r \geq 3$ repetitions are adopted [29]. In this study, only data from the last 4 years (2012–2015) was available, as a result $r = 4$. The present analysis will evaluate $p = 12$ *parts*, determined by the wind average speeds in each month of the year (January–December); $o = 4$ operators, which will be the four states, where wind average speeds were obtained through anemometry measurements by Energetic Research Company (EPE).

The monthly wind mean speed (m/s) data in homogeneous heights refer to the Anemometry Measurements Monitoring (AMA) by EPE [31], calculated in 63 stations located on the four states under analysis. The EPE [31] anemometric system receives, on a biweekly basis, standardized files containing the measurements taken in the same period in each anemometric station. The stations are composed of at least two anemometers, two wind vanes, one barometer, one thermometer and one hygrometer.

Table 2 contain measurements performed by EPE [31] for the states of Bahia (BA), Ceara (CE), Rio Grande do Norte (RN) and Rio Grande do Sul (RS), respectively. These data can also be seen in the time series plots for each Brazilian State of Fig. 1.

3. Results and discussion

Analysis of the measurement system indicates that the major part of variability is related to the "between months within states" variation, as it can be observed on Table 3. Concerning the results of ANOVA test, described by Eq. (1), both for comparison between the months (within states) and for states, the *p-value* found was 0.000, showing significant difference between wind mean speed over the months, during the years of 2012–2015, and between the analyzed states (see Table 4). It is worth mentioning that the MS results presented in Table 4 were obtained by using Eqs. (7)–(9).

The percentage of 69.81% obtained by Eq. (10) for the NGR & R shows that the measurement system is unacceptable, indicating significant differences on wind average speeds between the analyzes states over the analyzed period. Using Eq. (11), the ndc index equals to 1 determines that the measurement system is unacceptable. This result was expected since the comparison of "between months variation" in relation to "months within states and repeatability variations" have been about the same, 0.916 and 0.893 (see Table 3), respectively. Number of distinct categories would be larger if this study was planned with similar states and with stable wind speed through years by month.

Reproducibility represents the source of major contribution to variation of the measurement system, which indicates that the geographic variable (location of the different Brazilian states) is responsible for most part of the variation. In relation to the annual wind mean speed on the four states, as demonstrated on Fig. 2, the state of Rio Grande do Sul is where mean speed is statistically different from the others.

Brazilian territory is of 8.5 million km^2. RS state is located in the south, while the other assessed states in the northeast. Due to the different geographic location, the behavior of the wind in the RS is different from the other states, and therefore with average annual wind speed lower. The results confirm that in different regions of Brazil there is a significant difference of wind potential.

Other inferences can be made based on "Month within State" plot,

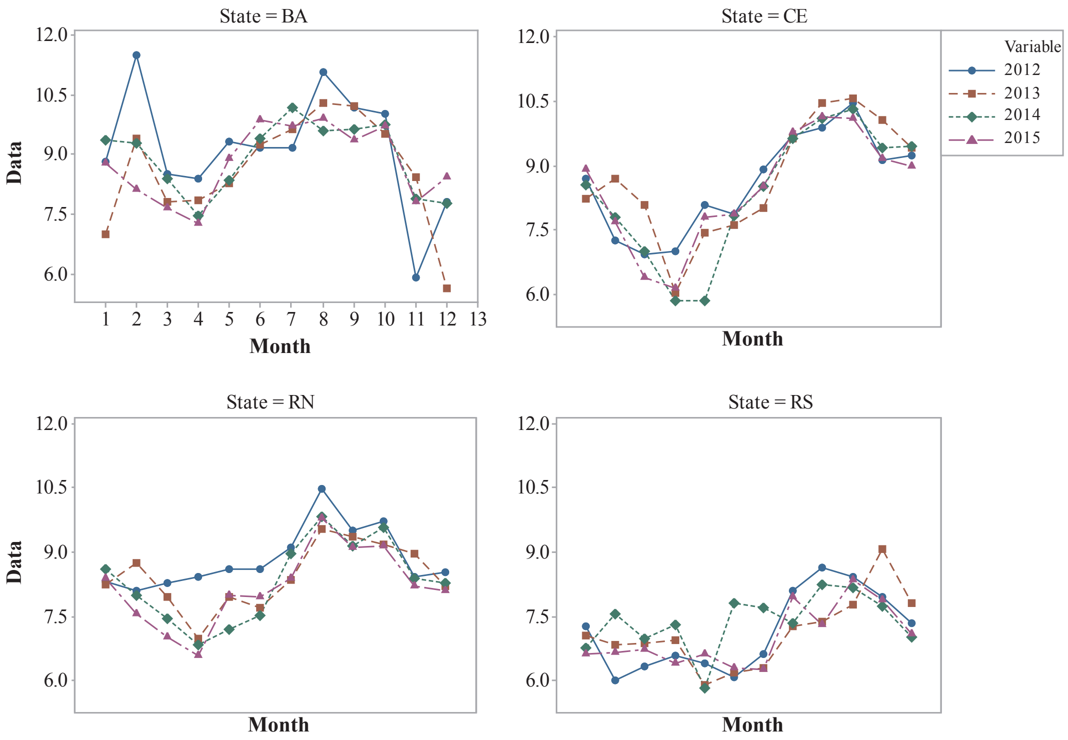

Fig. 1. Time series plots by year for each Brazilian State.

Table 3
Result of the variation found on the measurement system.

Variation source	StdDev	Contribution to the variation (%)
Between months	0.916	71.60
NGR & R	0.893	69.81
Repeatability	0.568	44.39
Reproducibility	0.689	53.88
Total	1.280	100.00

Table 4
Analysis of variance for the measurement system.

Source	DF	SS	MS	F	P
State	3	79.603	26.534	7.198	0.000
Month (State)	44	162.191	3.686	11.409	0.000
Repeatability	144	46.527	0.323		
Total	191	288.322			

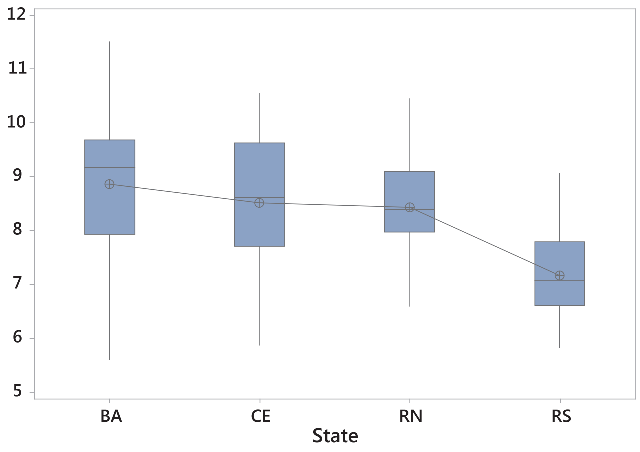

Fig. 2. Wind mean speed per state.

illustrated on Fig. 3. In Bahia state (BA), the wind speed presented high averages on winter and spring months, and between November and December the wind speed decreased, representing the period with the lowest averages in this state. The state of Ceara (CE) is the location with more accentuated difference between wind average speeds over the months. September to October was the period of highest wind average speeds occurrence, while in April the wind speed dropped sharply. In Rio Grande do Norte (RN), wind mean speed presented a behavior similar to CE, given that the wind power potential of these states are located on close coastal regions. Nevertheless, in RN wind mean speed variation was the lowest over the different months of the year.

The state of Rio Grande do Sul (RS) presents the lowest wind average speeds, however its variability between speeds over the year is the smallest. In spite of its lower speed averages in comparison to the other states, its small variability provides an important advantage to wind power producers, since it enables a more regular power generation. This fact generates a lower risk of noncompliance with power physical warranty to be fulfilled by the wind power plants, which is based on the generation average capacity over the year. Hence, producers are less exposed to having to liquidate generation noncompliance differences on the short-term market. The opposite occurs in CE, where variability is high over the year, which raises the probability that producers do not comply with the minimum supply warranty on months of lower wind average speed.

To investigate wind speed range by state and by month, the R chart was adopted. Control limits were obtained by Eqs. (12)–(14). Through graphic R (Fig. 4), it is possible to observe that the higher amplitudes, regarding wind average speeds measured for each month during these four years, occurred in the state of Bahia during summer months. In the state of Ceara it is noticeable a more accentuated amplitude in one month, even though over the other months, and in the states of Rio Grande do Norte and Rio Grande do Sul, amplitude did not exceed the specification limits of the measurement system. High amplitudes occurrence of wind average speed for one determined month in different years may be due to weather events that alter wind behavior, such as the *El Niño* and *La Niña* phenomena. However, in order to better analyze this matter, a larger amount of repetitions would be ideal, which,

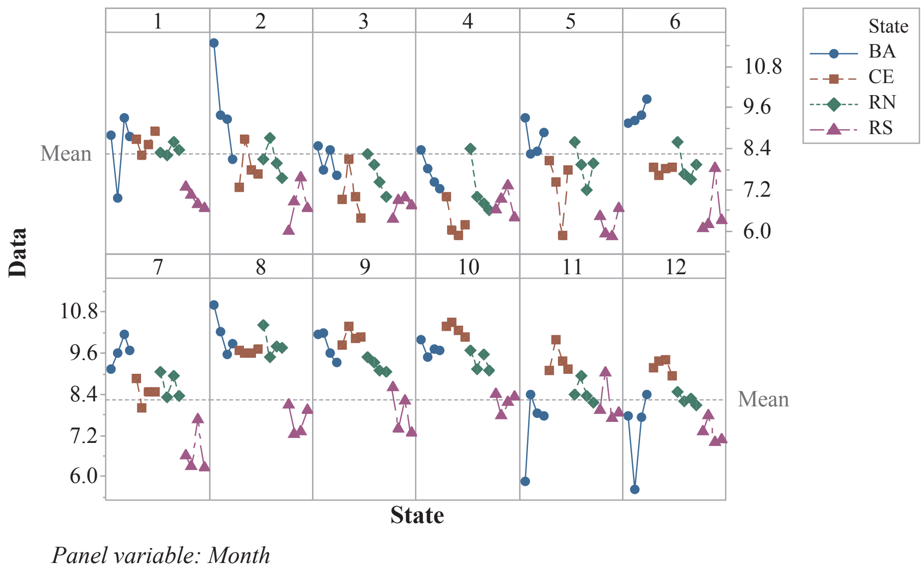

Fig. 3. Months within states plot for the mean of wind speed.

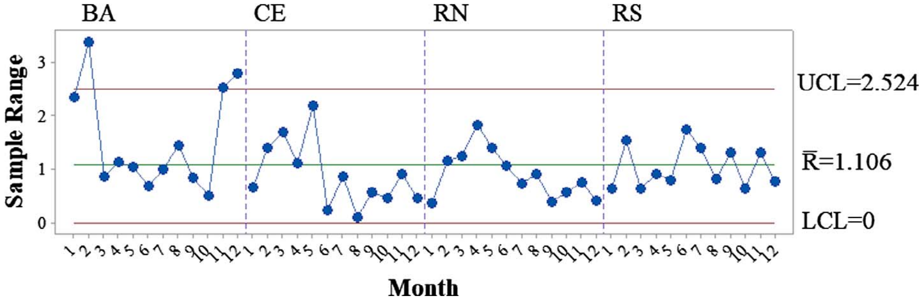

Fig. 4. R chart for the analyzed states.

in this case, corresponds to more years of monthly evaluation of wind average speeds.

Fig. 5 shows the time series plot of wind average speed for each Brazilian State. Again, it can be seen that monthly averages for the state of Rio Grande do Sul fairly differ from the other states. It is also possible to notice that, even though Ceara and Rio Grande do Norte averages are not punctually identical; they are similar in terms of the mean speed changes that occur over the months.

In the state of Bahia, given that the location of a great part of wind power plants is not on coastal regions, the monthly wind average speeds diverge more in relation to the two other northeastern states, however, alterations during each month are not so different from the ones occurring in Ceara and Rio Grande do Norte. Moreover, the state of Bahia presented the highest average speed on most of the months, which explains the fact that this state is the place where annual average capacity of wind power plants is higher. The wind average speeds reached lower levels than the other states only in the period between September and January.

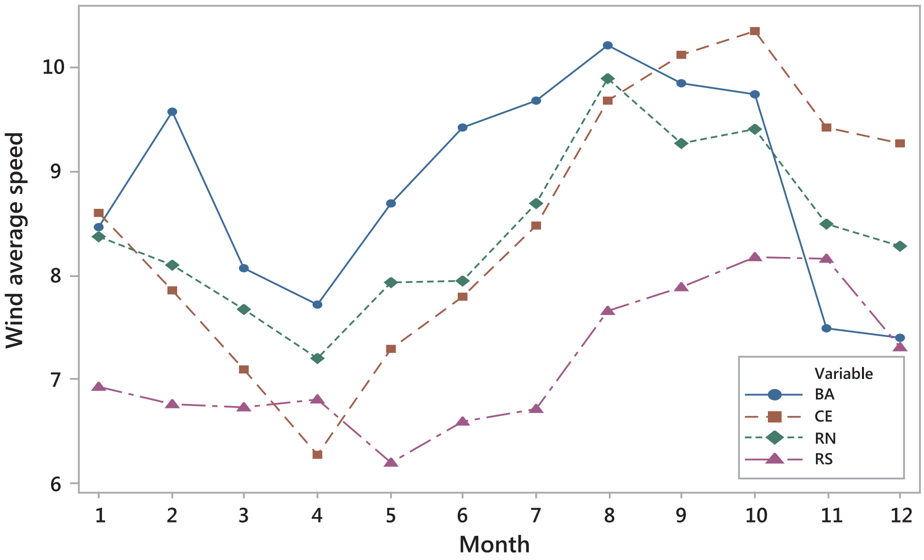

Fig. 5. Time series plot for wind average speed for each state.

July to October is the period when wind average speeds are higher in the northeastern states, a period of dry months, such as July and August, when rain is sparse and reservoirs of hydroelectric power plants are more compromised. In this context, it is possible to infer that the analyzed northeastern states are appropriate for lodging wind power plants as a reserve source for periods of drought.

4. Conclusions

The present study aimed to use a measurement system applied on the quality management field to perform a behavioral analysis of wind average speed at the four states which most produce wind power in Brazil, during the years of 2012–2015. Differently than when applied on quality management, the non-acceptance of the measurement system allows reaching important conclusions over wind speed behavior in different regions of Brazil.

Measurement system analysis NGR & R confirmed the monthly speed differences between medium to long-term due to seasonality. Furthermore, it was noticed that reproducibility, represented by measurements performed on four different states, was determinant to detect statistical differences of average speed measurements at the four analyzed states. It is important to emphasize that repeatability, that is, the performance of repeated measures for each month during four years (2012–2015), also presented significant statistical differences, although in a smaller proportion than reproducibility did.

The Xbar and interaction graphics between states and months enable to conclude that the state of Rio Grande do Sul presented lower wind average speed that the other states over the years. Nevertheless, wind speed variation in Rio Grande do Sul over the months is smaller than in the other states and, consequently, the producers are less exposed to the risk of liquidating generation differences during the year. Moreover, it is noticeable that the period when the states of Bahia, Ceara and Rio Grande do Norte present higher wind average speed includes dry months (July and August), which reveals the wind potential of these states to explore the wind power source as backup power.

Through graphic R, the main observation is that the highest amplitudes for repeated monthly measurements occurred in the state of Bahia, between the months of November and February. A possible cause for the presented amplitude is the occurrence of weather phenomena in the period, which alter wind behavior. However, in order to obtain more accurate conclusions, it is necessary to replicate the study in the future, on a range of years wider than four years.

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