
FUZZY CONTROL CHART: GRAPHICAL INTERFACE IN R FOR MONITORING PROCESS

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ABSTRACT

Control charts are the primary tool within statistical process control (SPC) used to monitor processes. Since sample data can include uncertainties arising from human subjectivity and measurement systems, fuzzy set theory can be applied to control charts when accurate data is not available. The values of the quality characteristic are fuzzified from the insertion of uncertainties and transformed into representative values in order to preserve the format of the control charts. This work proposes the use of fuzzy logic to control charts for monitoring the mean and range of univariate processes, as well as the creation of a computer interface in R language, through the Shiny package, capable of facilitating the user experience in the junction of the concepts presented.

KEYWORDS. Control chart. Fuzzy logic. R programming language.

1. Introduction

Statistical process control (SPC) is a set of techniques applied to monitor quality characteristics in order to improve productivity and product quality that came into use when Shewhart developed the first control charts.

Control charts can be defined as visual tools for monitoring quality characteristics of products and processes. It is possible through such a tool to quickly identify changes or special causes in the production line. Once a special cause is detected, its correction must be performed [Samohyl 2009].

According to [Shabani et al. 2017], traditional control charts are constructed using precise data. However, real-world data is extremely complicated to handle, as it involves a certain level of uncertainty, coming from both human judgments and measurement instruments. In this case, traditional Shewhart charts should not be used. One way to account for this real-world uncertainty is to apply the fuzzy set theory proposed by [Zadeh 1965] to model uncertainty and provide greater flexibility for control limits.

It is observed in recent years in the literature, a growing number of works about fuzzy control charts. [Wang and Raz 1990] proposed an approach based on fuzzy set theory to construct attribute control charts from linguistic data. They presented four transformation methods to calculate representative values, that is, four ways to convert fuzzy sets into scalar values. The representative values are plotted on the chart, keeping the traditional control chart format. [Senturk and Erginel 2009] used one of these transformation methods, the midrange transformation, to construct the control charts for variables: the $\bar{X}$ -R and the $\bar{X}$ -S with α -cuts. [Mendes et al. 2019] studied performance through of a fuzzy control chart by the average run length (ARL) and the extra quadratic loss (EQL). Observed that the fuzzy control chart has greater efficiency than the traditional control chart. [Ozdemir 2021] developed fuzzy $\bar{X}$ -S control charts with variable sample sizes for triangular fuzzy numbers. The capability analysis was performed in order to measure the performance of the process. [Ahmad and Cheng 2022] developed fuzzy control chart based on fuzzy process capability indices (FCPI) using triangular fuzzy numbers (TFNs). α -cut theory is applied in statistical quality control for fuzzy process control industrial application.

The use of software and statistical packages for data analysis and statistical process control is of great importance, from the development, application of the method to analysis and interpretation of results. Usually, such software has a relatively high acquisition cost, so the demand for free software is great nowadays [Mello and Peternelli 2013].

The aim and innovation of this study is the creation of the computational interface in R programming language using the Shiny package, since although they are widely applied, fuzzy control charts can seem complex because many people are not familiar with mathematics and statistics, including organizations. The computational interface to facilitate the user experience at the junction of the concepts presented here, fuzzy logic and control charts for variables, and use a free software.

2. Fuzzy control charts

Let X be a classical set formed by objects (x), also called universe of discourse. The fuzzy set A on X can be defined as a set of ordered pairs, as described in equation (1):

$$A = \{(x, \mu_A(x)) \mid x \in X\} \quad (1)$$

where $\mu_A(x)$ is called the "membership function" for the fuzzy set A .

This pertinence function $\mu_A(x)$ demonstrates the degree of pertinence between x and A , and the degree can vary in the interval $[0, 1]$.

A triangular fuzzy number is represented by (a, b, c) . The membership function will be given by expression (2).

$$\mu(x) = \begin{cases} \frac{x-a}{b-a}, & a \leq x \leq b, \\ 1, & x = b = c, \\ \frac{d-x}{d-c}, & c \leq x \leq d, \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

According to [Kaya and Kahraman 2011], when using a measurable quality characteristic, the triangular fuzzy number is best suited since it represents "approximately x" measurements. Figure 1 illustrates a triangular fuzzy number.

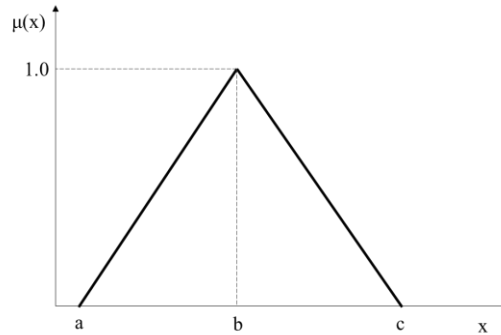


Figure. 1 Representation of a triangular fuzzy number

Using fuzzy arithmetic, the mean of each subgroup and general means of the samples can be computed by equations (3) and (4) respectively:

$$\bar{X}_{kj} = \frac{\sum_{i=1}^n X_{kji}}{n}; k = a, b, c; i = 1, 2, \dots, n; j = 1, 2, \dots, m, \quad (3)$$

$$\bar{\bar{X}}_{kj} = \frac{\sum_{j=1}^m \bar{X}_{kj}}{m}; k = a, b, c; j = 1, 2, \dots, m, \quad (4)$$

Once the maximum and minimum fuzzy observations are decided, the fuzzy range can be determined by the following equation (5).

$$R_{aj} = X_{\max,aj} - X_{\min,cj}; R_{bj} = X_{\max,bj} - X_{\min,bj}; R_{cj} = X_{\max,cj} - X_{\min,aj}; j = 1, 2, \dots, m, \quad (5)$$

where $(X_{\max,aj}, X_{\max,bj}, X_{\max,cj})$ is the maximum fuzzy number of the sample and $(X_{\min,aj}, X_{\min,bj}, X_{\min,cj})$ is the minimum fuzzy number of the sample, so the average range can be obtained according to equations (6), (7) and (8).

$$\bar{R}_a = \frac{\sum R_{aj}}{m} \quad (6)$$

$$\bar{R}_b = \frac{\sum R_{bj}}{m} \quad (7)$$

$$\bar{R}_c = \frac{\sum R_{cj}}{m} \quad (8)$$

The control limits for the fuzzy $\bar{X}$ control chart can be calculated as follows:

$$UCL_{\bar{X}} = (\bar{\bar{X}}_a, \bar{\bar{X}}_b, \bar{\bar{X}}_c) + A_2(\bar{R}_a, \bar{R}_b, \bar{R}_c) \quad (9)$$

$$CL_{\bar{X}} = (\bar{\bar{X}}_a, \bar{\bar{X}}_b, \bar{\bar{X}}_c) \quad (10)$$

$$LCL_{\bar{X}} = (\bar{\bar{X}}_a, \bar{\bar{X}}_b, \bar{\bar{X}}_c) - A_2(\bar{R}_a, \bar{R}_b, \bar{R}_c) \quad (11)$$

where A_2 is a coefficient that depends on the sample size n .

The control limits for the fuzzy R control chart can be calculated as follows:

$$UCL_R = D_4(\bar{R}_a, \bar{R}_b, \bar{R}_c) \quad (12)$$

$$CL_R = (\bar{R}_a, \bar{R}_b, \bar{R}_c) \quad (13)$$

$$LCL_R = D_3(\bar{R}_a, \bar{R}_b, \bar{R}_c) \quad (14)$$

where D_3 and D_4 are a coefficient that depends on the sample size n .

3. Fuzzification and defuzzification method

In this paper, the fuzzifications of the crisp observations for triangular fuzzy number can be obtained using the equations (15), (16) and (17).

$$a_j = b_j - \text{res} \times \text{runif}_j \quad (15)$$

$$b_j = b_j \quad (16)$$

$$c_j = b_j + \text{res} \times \text{runif}_j \quad (17)$$

where res is given by the instrument resolution used in the measurement of the quality characteristic and runif_j is a random number generated according to a uniform distribution.

It is possible to create fuzzy control charts by converting the fuzzy numbers into representative values using various transformations. Several defuzzification techniques have been proposed in the literature, such as: fuzzy median; α -level fuzzy midrange; fuzzy average; and fuzzy mode. In this work, the α -level fuzzy midrange is used [Kaya et al. 2017].

Such a transformation, α -level fuzzy midrange f_{mr}^α , can be defined as the midpoint of the end of the α -cut. The α -cut, denoted by B^α , is a set of values that have membership degrees greater than or equal to α , where a^α and c^α are the end points. Equation (18) describes this transformation.

$$f_{mr}^\alpha = \frac{1}{2}(a^\alpha + c^\alpha) \quad (18)$$

Applying the transformation to a sample j gives the statistic for each sample, called $S_{mr,j}^\alpha$, according to equation (19).

$$S_{mr,j}^\alpha = \frac{(a_j + c_j) + \alpha[(b_j - a_j) - (c_j - b_j)]}{2} \quad (19)$$

The α -cut value can vary from 0 to 1 and indicates the amount of uncertainty in the process: the higher its value, the lower the uncertainty [Fadei and Pooya 2018].

According to [Senturk and Erginel 2009], α -cut fuzzy midrange control limits for α -cut fuzzy control charts are calculated as shown in equations (20), (21), (22), (23), (24) and (25).

$$UCL_{mr-\bar{X}}^\alpha = \left(\frac{\bar{X}_a^\alpha + \bar{X}_c^\alpha}{2}\right) + A_2 \left(\frac{\bar{R}_a^\alpha + \bar{R}_c^\alpha}{2}\right) \quad (20)$$

$$CL_{mr-\bar{X}}^\alpha = \left(\frac{\bar{X}_a^\alpha + \bar{X}_c^\alpha}{2}\right) \quad (21)$$

$$LCL_{mr-\bar{X}}^\alpha = \left(\frac{\bar{X}_a^\alpha + \bar{X}_c^\alpha}{2}\right) - A_2 \left(\frac{\bar{R}_a^\alpha + \bar{R}_c^\alpha}{2}\right) \quad (22)$$

$$UCL_{mr-R}^\alpha = D_4 \left(\frac{\bar{R}_a^\alpha + \bar{R}_c^\alpha}{2}\right) \quad (23)$$

$$CL_{mr-R}^\alpha = \left(\frac{\bar{R}_a^\alpha + \bar{R}_c^\alpha}{2}\right) \quad (24)$$

$$LCL_{mr-R}^\alpha = D_3 \left(\frac{\bar{R}_a^\alpha + \bar{R}_c^\alpha}{2}\right) \quad (25)$$

The values of $\bar{X}_a^\alpha$, $\bar{X}_c^\alpha$, $\bar{R}_a^\alpha$ and $\bar{R}_c^\alpha$, respectively can be obtained by:

$$\bar{X}_a^\alpha = \bar{X}_a + \alpha(\bar{X}_b - \bar{X}_a) \quad (26)$$

$$\bar{X}_c^\alpha = \bar{X}_c - \alpha(\bar{X}_c - \bar{X}_b) \quad (27)$$

$$\bar{R}_a^\alpha = \bar{R}_a + \alpha(\bar{R}_b - \bar{R}_a) \quad (28)$$

$$\bar{R}_c^\alpha = \bar{R}_c - \alpha(\bar{R}_c - \bar{R}_b) \quad (29)$$

According to the limits calculated above, the process control condition can be defined as: in-control, if $UCL_{mr-\bar{X}}^\alpha \leq S_{mr-\bar{X}}^\alpha \leq LCL_{mr-\bar{X}}^\alpha$, and out-of-control otherwise for the fuzzy $\bar{X}$ control chart and in-control, if $UCL_{mr-R}^\alpha \leq S_{mr-R}^\alpha \leq LCL_{mr-R}^\alpha$, and out-of-control otherwise for the fuzzy R control chart.

4. Computational interface for fuzzy control chart

RStudio software, an integrated development environment using the public domain R language, has been gaining more and more followers. The R language can be considered high-level and capable of analyzing data and generating graphics. It has open-source code, so it can be modified, or implemented with new procedures by any user. Moreover, R is able to interact with several other programs and programming languages [Mello and Peternelli 2013].

RStudio is composed of several packages, also called library. Packages are a set of commands and or data sets. Shiny is an R language package used for web application development, without the need for much knowledge of computing or website development languages. In a simple way it allows to create an interface in which users can interact with data in a responsive way, that is, any new data insertion or modification the application will respond quickly.

The development of a graphical interface for free access is interesting since it facilitates the user's contact with statistical process control, in this case, more specifically, the fuzzy control chart. The interface integrates the concepts of control charts with fuzzy logic in a practical way. Its implementation eliminates the need for the user to have knowledge about programming or mathematical concepts to obtain a tool for statistical process control.

In the development of the graphical interface of this paper, the programming language R and particularly the package Shiny were used.

When accessing the interface, the user is faced with the initial screen, in the "Start" tab. This screen was created with the intention of giving a brief explanation about the objective of the interface. One can notice the presence of the logo of the Guaratinguetá School of Engineering and Sciences (UNESP-FEG), where the author studies, and of the Coordenação de Aperfeiçoamento de Pessoal do Ensino Superior (CAPES), which finances the Postgraduate Engineering Program.

On the left side you can see the name of the developers and the link for the user to download a User's Guide for the computer interface. Figure 2 and 3 illustrates the User's Guide and Figure 4 illustrates start screen.



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Fuzzy Control Chart for Variables

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Presentation

Quality is one of the most important factors in consumers' decision to purchase products and services. Organizations must constantly apply quality control tools to ensure that products and services are tailored to customer desires and market specifications. Statistical process control (SPC) is a set of tools that uses statistical techniques to monitor processes.

Control charts, developed by Shewhart, are primarily intended to control process variability. Due to its easy implementation and interpretation, it can be applied in many areas to improve the productivity and quality of production processes.

In the real world, data involves a certain level of uncertainty coming from both human judgments and measuring instruments. In this case, traditional Shewhart control charts may not be as effective for monitoring the process, since they are constructed using precise data. For this purpose, fuzzy control charts should be used.

This free interface was built for anyone to enter data from a univariate process and monitor the mean and variability by entering uncertainties using Fuzzy Control Charts.

Computational Interface Objectives

Make it possible for users working in an industrial/operational environment to perform statistical process control in a fast and simplified way.

Functions

1. Insertion data in .xlsx format (Excel® spreadsheets);
2. Fuzzification of the spreadsheet data from the resolution of the instrument used to measure the quality characteristic applied as a limiter for a uniformly distributed random variable;
3. Calculation and defuzzification of all variables needed to obtain the control limits (LCL, CL and UCL) and the observations to be plotted;

OBSERVATION: for the defuzzification process the user must enter the alpha value. The alpha value must vary from 0 to 1.

It is important to emphasize that the smaller the alpha the more uncertainty the process will have, thus $\alpha=1$ corresponds to the traditional control chart. The user, or quality specialist will have to choose alpha according to the quantity of uncertainty present in his process.



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4. Preparation of a histogram and QQ-plot to be able to identify the degree of normality of the spreadsheet data;
5. Shapiro-Wilk normality test showing the p-value.
OBSERVATION: if p-value > 0.05, the data follow a normal distribution.
6. Elaboration of fuzzy $\bar{X} - R$ control charts, according to the user's need and/or process characteristics.

Steps for use:

1. Insert in the tab Statistical Process Control the resolution value of the instrument used to measure the quality characteristic. Insert the value of alpha.
2. In the Statistical Process Control tab, insert the data referring to phase I. You must plot the fuzzy control chart of phase I and Histogram with QQ-Plot to analyze the normality of the data from phase I. If the process is in control, you must enter the data referring to phase II and must plot the fuzzy control chart of phase II and Histogram with QQ-Plot to analyze the normality of the data from phase II. If you detect that the process is out of control in phase I, you must review your data before plotting the control chart of phase II.
3. The spreadsheet of data entered in Excel® format must follow this format:

	A	B	C	D	E
1	x1	x2	x3	x4	x5
2	74.030	74.002	74.019	73.992	74.008
3	73.995	73.992	74.001	74.011	74.004
4	73.988	74.024	74.021	74.005	74.002
5	74.002	73.996	73.993	74.015	74.009

OBSERVATION: Both the phase I and phase II fuzzy control charts display the values of the upper, lower, and center line control limits. Since the fuzzy control charts and normality analyses are plotted in a new window, it is possible for the user to save them in familiar formats such as .pdf and .jpeg image format for later use. Simply click "File" and then "Save As" and the options for saving will appear.

Fuzzy Control Chart

Developers

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Download the User Guide here [Download](#)

Start **Statistical Process Control**

This free interface was built so that anyone can enter data from a univariate process and monitor the mean and variability using Fuzzy Control Charts






Figure. 4 Start screen

The section Statistical Process Control section is dedicated to the analyses that will be performed. Insertion of the resolution of the instrument used in the measurement of the quality characteristic, alpha value and insertion of data from phase I and phase II through a spreadsheet in Excel ® format (.xlsx) and plotting the fuzzy control chart for both phases. Figure 5 illustrates the Statistical Process Control section in general.

Fuzzy Control Chart

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Start **Statistical Process Control**

Enter the value of the instrument's resolution

0,01

Enter the value of alpha

0,95

Enter the Data Sheet for Phase I (xlsx)

Browse... No file selected

Plot Phase I Fuzzy Control Chart Histogram and QQ-Plot Phase I Data

Enter the Data Sheet for Phase II (xlsx)

Browse... No file selected

Plot Phase II Fuzzy Control Chart Histogram and QQ-Plot Phase II Data

Figure. 5 Statistical Process Control section

It is also possible in this same tab to perform a normality analysis of the data using the histogram and the QQ-plot. The QQ-plot provides a distribution of cumulative percentages, also called a normal probability plot. If the points on the graph follow a pattern approximating a straight line, the data in question have an approximately normal distribution.

Along with the histogram and QQ-plot the interface also shows the p-value calculated using the Shapiro-Wilk normality test. When the p-value is greater than 0.05 the data can be considered normal.

After entering the data in phase I, for the chart to be constructed and visualized, the practitioner simply enters the values for his or her samples in the and clicks on the button Plot Fuzzy Control Chart Phase I. For the normality analysis of such data the user should click Histogram and QQ-Plot Phase I. Figure 6 illustrates the graphs generated for normality analysis of the Phase I data.

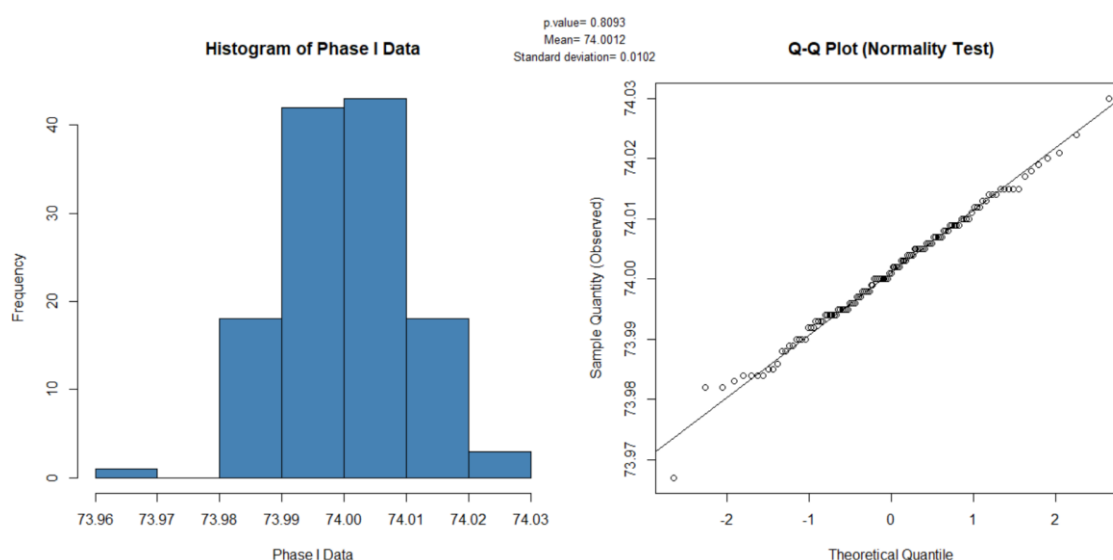


Figure. 6 Graphs generated for normality analysis of the Phase I data

It is emphasized the use of fuzzy control charts involves the applications of phases I and II. In phase I, a set of data is collected in order to construct the control limits. For the control limits to be valid for future production monitoring the process must be in control. If there are any outliers, they must be removed, and the control limits recalculated. The goal of the analysis in phase I is to bring the process to the control state. Phase II begins after having a "clean" set of data, the process is assumed to be reasonably stable, the sample statistics for each sample drawn from the process is compared with the control limits. Special causes that result from small changes in the process are expected in phase II, since heavier variabilities have already been removed in phase I, see [Montgomery 2016]. Figure 7 illustrates an example of a fuzzy control chart $\bar{X}$ -R of phase I.

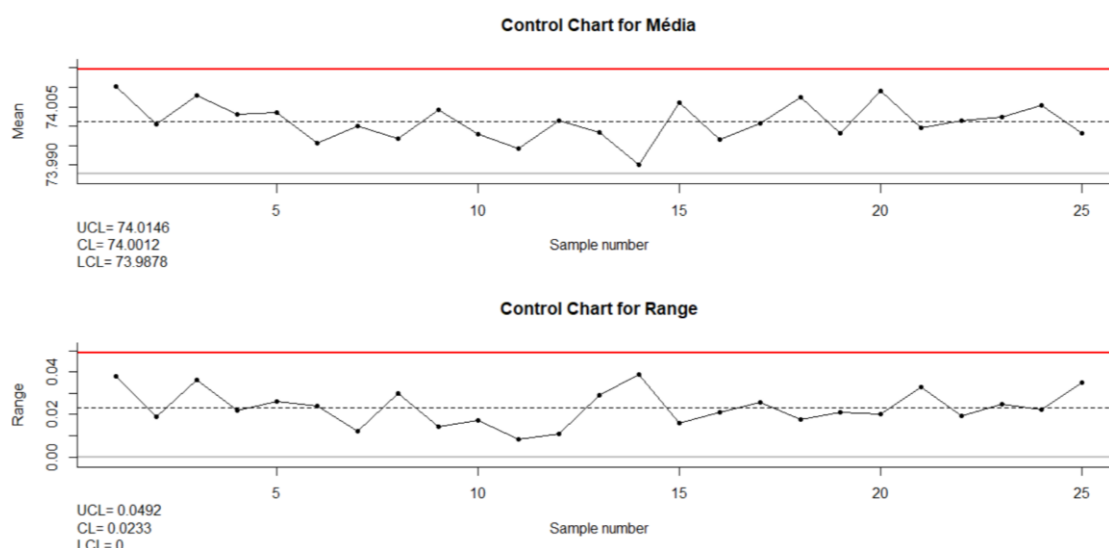


Figure. 7 Example of a fuzzy control chart $\bar{X}$ -R of phase I

After entering and verifying the data in phase I, the user can now start monitoring his process in phase II. This is the step where new data is entered in real time as new samples are generated. For the chart to be built and viewed, the practitioner simply enters the values for his samples and clicks the button Plot Fuzzy Control Chart Phase II. For the normality analysis of such data the user should click Histogram and QQ-Plot Phase II. Figure 8 illustrates the graphs generated for normality analysis of the phase II data and Figure 9 illustrates an example of a fuzzy control chart $\bar{X}$ -R of phase II.

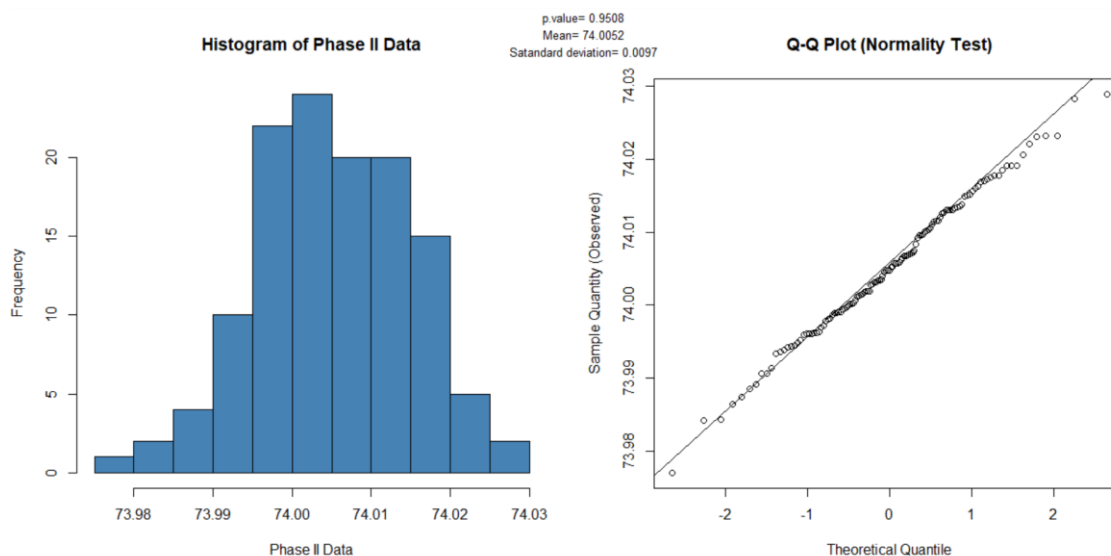


Figure. 8 Graphs generated for normality analysis of the phase II data

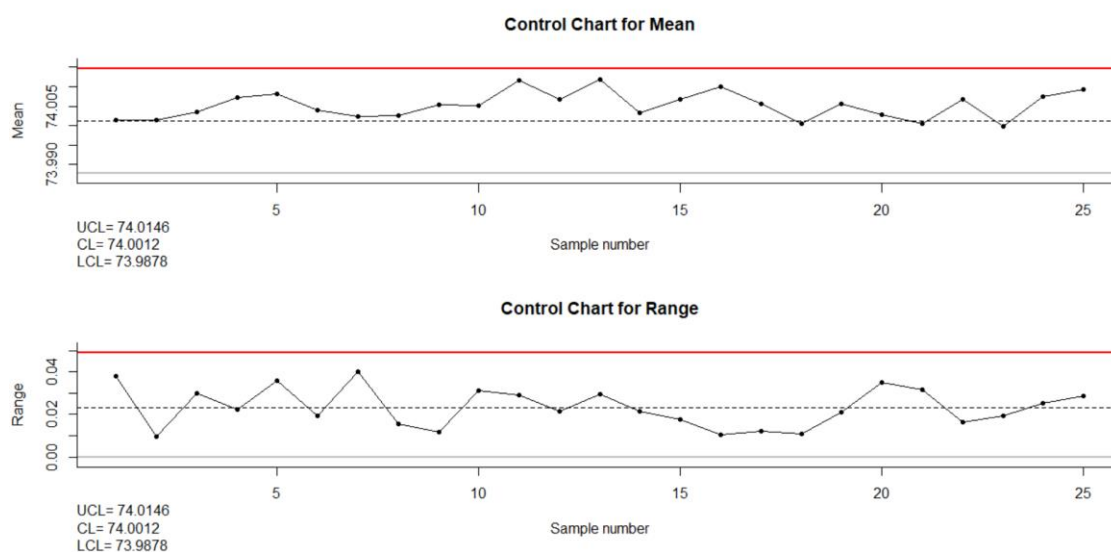


Figure. 9 Example of a fuzzy control chart $\bar{X}$ -R of phase II

Both the phase I and phase II fuzzy control charts present the values of the upper, lower, and center line control limits. Since the fuzzy control charts and normality analyses are plotted in a new window, it is possible for the user to save them in familiar formats such as .pdf and .jpeg image format for later use. Figure 10 illustrates such functionality.



Figure. 10 Formats for saving generated charts

5. Conclusions

Through the results presented, it can be concluded that the interface created is capable of fuzzifying crisp observations and defuzzifying intuitionistic fuzzy observations, performing a normality analysis of the data, calculating control limits, and plotting control charts from information provided by the user. The R language was chosen because it can be considered high-level and capable of analyzing data and generating graphs. It has open-source code, and can be modified, or implemented with new procedures by any user.

The application of fuzzy logic to traditional control charts becomes interesting, since it considers the uncertainty of the process. The use of the fuzzification method proposed in this work makes the process closer to reality since it uses the resolution of the instrument as a source of uncertainty. Fuzzy observations and fuzzy control charts can provide more flexibility to control a process since quality experts can vary the degree of uncertainty α -cut inserted in the process.

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