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Constructing the nonlinear regression equations based on multivariate normalizing transformations

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In the paper we consider the techniques to construct the equations, confidence and prediction intervals of nonlinear regressions on the basis of multivariate normalizing transformations for non-Gaussian data. We demonstrate that the poor normalization of multivariate non-Gaussian data using the univariate transformations leads to an expansion of the confidence and prediction intervals of non-linear regression for a larger number of data rows compared to the multivariate normalizing transformation.

**Keywords:** non-linear regression equation, confidence interval, prediction interval, normalizing transformation, multivariate non-Gaussian data.

В статі розглядаються методи побудови рівнянь, довірчих інтервалів та інтервалів передбачення нелінійних регресій на основі багатовимірних нормалізуючих перетворень для негаусовських даних. У якості прикладу побудовано нелінійне регресійне рівняння для оцінювання розміру програмного забезпечення інформаційних систем з відкритим кодом на PHP із застосуванням багатовимірного нормалізуючого перетворення Джонсона для сімейства *SB*. Це рівняння отримано за вибіркою чотиривимірних негаусовських даних: фактичний розмір програмного забезпечення у тисячах рядків коду, загальна кількість класів, загальна кількість зв'язків та середня кількість атрибутів на клас у концептуальній моделі даних з 32 інформаційних систем, розроблених з використанням мови програмування PHP. Попередньо зазначені дані були перевірені на наявність викидів із використанням квадрату відстані Махаланобиса (Mahalanobis): для рівня значимості, що дорівнює 0,005, викиди відсутні. Гіпотезу про багатовимірну нормальність було перевірено за критерієм квадрату відстані Махаланобиса. Побудоване нелінійне рівняння у порівнянні з іншими регресійними рівняннями (як лінійними, так і нелінійними, які отримані за допомогою одновимірних нормалізуючих перетворень Джонсона та десяткового логарифму) має більший множинний коефіцієнт детермінації і менше значення середньої величини відносної похибки. Продемонстровано, що погана нормалізація багатовимірних негаусовських даних за допомогою одновимірних перетворень або її відсутність призводить до збільшення ширини довірчих інтервалів та інтервалів передбачення як нелінійної так і лінійної регресії для більшої кількості рядків даних у порівнянні з багатовимірним нормалізуючим перетворенням.

**Ключові слова:** нелінійне рівняння регресії, довірчий інтервал, інтервал передбачення, нормалізуюче перетворення, багатовимірні негаусовські дані.

1 Introduction

A normalizing transformation is a good way to construct equations, confidence and prediction intervals of non-linear regressions [1-5], and it is often used in information technology, software engineering, biometry, ecology, finance, etc. According to [3] the transformations are mainly used for four purposes, two of which are: the first – to obtain approximate normality for the distribution of the residuals, the second – to transform the dependent and independent random variables in such a way that the strength of the linear relationship between new variables (normalized variables) is better than the linear relationship between the response and the predictor (or predictors) without transformation. Well-known techniques to construct the equations, confidence and prediction intervals of nonlinear regressions are based on the univariate normalizing transformations, which do not take into account the correlation between dependent and independent variables when multivariate non-Gaussian data is normalized. Therefore the multivariate normalizing transformations needs to be applied.

2 Unsolved problems and objectives of the paper

Well-known techniques for constructing the non-linear regression equations are based on the univariate normalizing transformations (such as, the decimal logarithm, the Box-Cox transformation), which do not take into account the correlation between the dependent and independent random variables in the case of normalization of multivariate non-Gaussian data. Application of such univariate normalizing transformations for building the nonlinear regression equations does not always lead to good multivariate normality and linear relationship between normalized variables. This demands the usage of the multivariate normalizing transformations. The objective of the paper is to consider techniques for constructing the equations, confidence and prediction intervals of multivariate nonlinear regressions on the basis of multivariate normalizing transformations. The nonlinear regression prediction results obtained by constructing the equations should be better in comparison with other nonlinear regression equations based on univariate normalizing transformations, primarily on such standard evaluations as the multiple coefficient of determination and mean magnitude of relative error. Application of multivariate normalizing transformations should lead to a narrowing of confidence and prediction intervals of nonlinear regressions for a larger number of data rows compared to the univariate normalizing transformations.

3 Problem statement

Suppose that there are bijective multivariate normalizing transformation of non-Gaussian random vector  to Gaussian random vector 

 (3.1)

and the inverse transformation for (3.1)

. (3.2)

Here  is the vector of normalizing transformation, . It is required to build the nonlinear regression equation in the form  on the basis of the transformations (3.1) and (3.2).

4 The techniques

The techniques to construct the equations, confidence and prediction intervals of nonlinear regressions are based on the nonlinear regression analysis using the multivariate normalizing transformations and they consist of three steps [5]. For the first step, a set of multivariate non-Gaussian data is normalized using a bijective multivariate normalizing transformation (3.1). In the second step, the equation, confidence and prediction intervals of linear regression for the normalized data are built. In the third step, the equations, confidence and prediction intervals of nonlinear regressions for multivariate non-Gaussian data are constructed on the basis of the equation, confidence and prediction intervals of linear regression for the normalized data and transformations (3.1) and (3.2).

The linear regression equation for normalized data will have the form [3]

, (4.1)

where  is a prediction result obtained by linear regression equation for values of components of vector ;  is the matrix of centered regressors that contains the values , , , ;  is estimator for vector of parameters of equation (4.1), .

The nonlinear regression equation will be

. (4.2)

The technique to construct a confidence interval of nonlinear regression is based on transformations (3.1) and (3.2), linear regression equation (4.1) and a confidence interval for normalized data. The confidence interval of nonlinear regression is

, (4.3)

where , ;  is a quantile of the Student *t*-distribution with  degrees of freedom and  significance level;  is the  matrix

,

where , .

The technique to construct a prediction interval of nonlinear regression is based on transformations (3.1) and (3.2), linear regression equation (4.1) and a prediction interval for normalized data. The prediction interval of non-linear regression is

. (4.4)

5 Examples

We consider the examples of constructing the equations, confidence and prediction intervals of nonlinear regressions for multivariate non-Gaussian data for two cases: univariate and multivariate normalizing transformations. Table 1 contains the data [6] on metrics of software for open-source PHP-based information systems.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | | Table 1. The data and prediction results by regression equations. | | | | | | | |
| *i* | *Y* in KLOC | |  |  |  | prediction results by regressions | | | |
| linear | non-linear regressions | | |
| **decimal logarithm** | **Johnson univariate** | **Johnson multivariate** |
| 1 | 3.038 | | 5 | 2 | 10.6 | 3.237 | 4.707 | 4.675 | 4.283 |
| 2 | 22.599 | | 17 | 7 | 7 | 24.142 | 22.681 | 19.965 | 21.048 |
| 3 | 32.243 | | 21 | 13 | 4.524 | 37.524 | 32.351 | 32.098 | 34.906 |
| 4 | 16.164 | | 13 | 11 | 7.077 | 25.916 | 20.232 | 23.171 | 23.191 |
| 5 | 83.862 | | 35 | 24 | 6.571 | 74.624 | 69.290 | 80.265 | 76.393 |
| 6 | 24.22 | | 13 | 9 | 8.077 | 23.224 | 19.275 | 20.524 | 20.495 |
| 7 | 63.929 | | 35 | 19 | 8.029 | 67.215 | 65.909 | 65.913 | 67.297 |
| 8 | 2.543 | | 5 | 3 | 9.4 | 4.127 | 5.297 | 5.789 | 5.029 |
| 9 | 6.697 | | 5 | 5 | 7 | 5.906 | 6.028 | 7.353 | 6.223 |
| 10 | 55.537 | | 25 | 14 | 8.64 | 46.843 | 43.089 | 42.098 | 45.209 |
| 11 | 55.752 | | 39 | 10 | 9.077 | 57.814 | 60.290 | 67.070 | 56.644 |
| 12 | 62.602 | | 30 | 17 | 7 | 56.995 | 53.494 | 53.497 | 56.727 |
| 13 | 67.111 | | 23 | 22 | 14.957 | 61.856 | 49.720 | 65.500 | 63.792 |
| 14 | 2.552 | | 3 | 1 | 8.333 | -2.395 | 2.179 | 2.202 | 2.324 |
| 15 | 12.17 | | 10 | 5 | 3.7 | 9.959 | 10.977 | 9.693 | 9.659 |
| 16 | 12.757 | | 13 | 9 | 5 | 21.218 | 18.042 | 18.682 | 19.002 |
| 17 | 5.695 | | 7 | 3 | 8.429 | 5.976 | 7.285 | 7.083 | 6.520 |
| 18 | 7.744 | | 9 | 6 | 9.222 | 13.991 | 11.914 | 12.911 | 11.988 |
| 19 | 7.514 | | 4 | 1 | 8 | -1.371 | 2.882 | 2.496 | 2.820 |
| 20 | 11.054 | | 9 | 9 | 3.667 | 15.385 | 12.006 | 13.301 | 12.884 |
| 21 | 29.77 | | 17 | 15 | 3.412 | 35.179 | 26.465 | 27.321 | 29.362 |
| 22 | 11.653 | | 9 | 8 | 8.778 | 17.045 | 13.020 | 15.461 | 14.338 |
| 23 | 6.847 | | 5 | 4 | 3.6 | 2.017 | 5.107 | 5.435 | 4.850 |
| 24 | 13.389 | | 7 | 5 | 11.714 | 11.462 | 9.033 | 10.367 | 9.102 |
| 25 | 14.45 | | 12 | 6 | 16.583 | 22.513 | 17.181 | 20.191 | 18.741 |
| 26 | 4.414 | | 6 | 3 | 3.667 | 1.630 | 5.575 | 5.318 | 4.966 |
| 27 | 2.102 | | 3 | 1 | 3.333 | -5.655 | 1.921 | 2.142 | 2.168 |
| 28 | 42.819 | | 20 | 18 | 3.5 | 43.975 | 33.150 | 37.967 | 40.170 |
| 29 | 4.077 | | 4 | 2 | 9 | 0.953 | 3.688 | 3.892 | 3.508 |
| 30 | 57.408 | | 33 | 14 | 9.242 | 57.164 | 57.273 | 53.121 | 55.910 |
| 31 | 7.428 | | 7 | 3 | 7 | 5.044 | 7.101 | 6.861 | 6.359 |
| 32 | 8.947 | | 15 | 5 | 4 | 16.360 | 16.585 | 12.934 | 13.808 |

Let us remind that ****** implies the actual software size in the thousand lines of code (KLOC), ,  and  determine respectively the total number of classes, the total number of relationships and the average number of attributes per class, that is, , where *A* is the total number of attributes in conceptual data model.

For normalizing the multivariate non-Gaussian data from Table 1, we use the Johnson translation system

~, (5.1)

where  is the *m*-dimensional vector of means equal to zero;  is the  covariance matrix with variances equal to one; ;  is one of the translation functions

 (5.2)

Here ; . In our case *X* equals *Y*, ,  or  respectively.

We use the technique [7] based on multivariate normalizing transformations and the squared Mahalanobis distance (MD) to detect the outliers in the data from Table 1. There are no outliers in the data from Table 1 after their normalization by the Johnson multivariate transformation (5.1) for  family for 0.005 significance level. The same result has been obtained for the transformation (5.1) for  family. In [6] it is also assumed that the data contains no outliers. The values of squared MD for data normalized by the Johnson univariate transformation for  family from Table 1 indicate that the data of systems 11 and 19 are multivariate outliers, since for these data rows the values of squared MD equal to 18.29 and 17.16 respectively are greater than the value of the quantile of the Chi-Square distribution, which equals to 14.86 for 0.005 significance level. Without using normalization, the data of system 11 is multivariate outlier, since for this data row the squared MD equals to 15.44. It should be noted that there are no outliers in the data from Table 1 after their normalization by the decimal logarithm transformation.

Estimators for parameters of the multivariate transformation (5.1) for  family have been calculated by the maximum likelihood method and are: , , , , , , , , , , , , , ,  and .

The sample covariance matrix  of the  is used as the approximate moment-matching estimator of covariance matrix 

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After normalizing the non-Gaussian data by the multivariate transformation (5.1) for  family the linear regression equation is built for normalized data

. (5.3)

Parameters of the equation (5.3) have been estimated by the least square method. The estimators for parameters of the equation (5.3) are: , ,  and .

After that the non-linear regression equation (4.2) is built

, (5.4)

where  is prediction result by the equation (5.3), ******, , .

The prediction results by nonlinear regression equation (5.4) for values of components of vector  from Table 1 are shown in the Table 1 for two cases: univariate and multivariate normalizing transformations. For univariate the Johnson normalizing transformations of  family (5.2) the estimators for parameters are: , , , , , , , , , , , , , ,  and . In the case of univariate normalizing transformations the estimators for parameters of the equation (5.3) are: , ,  and .

Also the nonlinear regression equation (4.2) is built by the decimal logarithm transformation

, (5.5)

where the estimators for parameters of the equation (5.5) are: , ,  and .

Table 1 also contains the prediction results by linear regression equation from [6] for values of components of vector  from Table 1. It should be noted that the prediction results obtained by the linear regression equation from [6] are negative for the three rows of data: 14, 19 and 27. All prediction results obtained by non-linear regression equations (5.4) and (5.5) are positive.

The values of multiple coefficient of determination , Mean Magnitude of Relative Error (MMRE) and Percentage of Prediction (PRED(0.25)) for the regression equations are shown in the Table 2.

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| --- | --- | --- | --- | --- |
| Table 2. Values of , MMRE and PRED(0.25) | | | | |
| Coefficients | Linear regression equation | Non-linear regression equations | | |
| univariate transformations | | multivariate transform. |
| logarithm | Johnson |
|  | 0.9491 | 0.9375 | 0.9591 | 0.9730 |
| MMRE | 0.4919 | 0.2455 | 0.2535 | 0.2243 |
| PRED(0.25) | 0.5313 | 0.6250 | 0.7188 | 0.6875 |

The acceptable values of MMRE and PRED(0.25) are not more than 0.25 and not less than 0.75 respectively. The values of MMRE are not more than 0.25 for nonlinear regression equation (5.4) on the basis of multivariate normalizing transformation and for non-linear regression equation (5.5) based on the decimal logarithm transformation. Although all values of PRED(0.25) in the Table 2 are less than 0.75 nevertheless the values are greater for nonlinear regression equation (5.4). All values of  in the Table 2 are greater than 0.75 but the value  is greater for nonlinear regression equation (5.4) on the basis of the Johnson multivariate transformation.

The confidence and prediction intervals of nonlinear regression are defined by (4.3) and (4.4) respectively for the data from Table 1. Table 3 contains the lower (LB) and upper (UB) bounds of the confidence intervals of linear and nonlinear regressions based on univariate and multivariate transformations respectively for 0.05 significance level. The values from Table 3 indicate that the lower bounds of the confidence interval of linear regression from [6] are negative for the seven rows of data: 1, 14, 19, 23, 26, 27 and 29. All the lower bounds of the confidence interval for nonlinear regression equations (5.4) and (5.5) are positive. For the fourteen rows of data the widths of the confidence interval of linear regression are greater than for nonlinear regressions. The widths of the confidence interval of nonlinear regression on the basis of the Johnson multivariate transformation are less than following the decimal logarithm univariate transformation for the seventeen rows of data: 1, 3, 5, 7-14, 19, 23, 26, 27, 29 and 30. The widths of the confidence interval of nonlinear regression on the basis of the Johnson multivariate transformation are less than following the Johnson univariate transformation for the twenty-four rows of data: 1-4, 6-12, 15-18, 20-26, 28-31. Approximately the same results are obtained for the prediction interval of regressions.

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| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Table 3. Bounds of the confidence intervals of regressions. | | | | | | | | |
| *i* | Bounds for linear regression | | Bounds for nonlinear regressions | | | | | | |
| decimal logarithm transformation | | Johnson univariate transformation | | Johnson multivariate transformation | | |
| LB | UB | LB | UB | LB | UB | LB | UB | |
| 1 | -0.402 | 6.877 | 3.725 | 5.947 | 3.673 | 6.267 | 3.532 | 5.370 | |
| 2 | 21.413 | 26.871 | 18.933 | 27.172 | 15.473 | 25.455 | 16.565 | 26.460 | |
| 3 | 34.344 | 40.704 | 26.415 | 39.621 | 24.791 | 40.266 | 28.688 | 41.670 | |
| 4 | 23.172 | 28.660 | 16.855 | 24.285 | 17.982 | 29.365 | 18.876 | 28.212 | |
| 5 | 69.187 | 80.062 | 55.076 | 87.173 | 74.107 | 83.078 | 67.843 | 82.455 | |
| 6 | 21.015 | 25.433 | 16.557 | 22.438 | 16.129 | 25.819 | 17.128 | 24.385 | |
| 7 | 62.690 | 71.740 | 52.309 | 83.045 | 56.434 | 72.961 | 59.139 | 74.114 | |
| 8 | 1.013 | 7.241 | 4.288 | 6.544 | 4.484 | 7.748 | 4.147 | 6.243 | |
| 9 | 3.084 | 8.728 | 4.569 | 7.951 | 5.456 | 10.203 | 4.848 | 8.199 | |
| 10 | 43.863 | 49.824 | 35.573 | 52.195 | 33.947 | 50.366 | 38.167 | 52.354 | |
| 11 | 49.560 | 66.068 | 41.448 | 87.698 | 42.891 | 79.359 | 39.199 | 71.614 | |
| 12 | 53.265 | 60.725 | 43.512 | 65.766 | 44.275 | 61.787 | 48.759 | 64.130 | |
| 13 | 54.146 | 69.566 | 35.747 | 69.156 | 49.897 | 75.572 | 48.637 | 75.635 | |
| 14 | -5.673 | 0.883 | 1.639 | 2.897 | 2.125 | 2.375 | 2.155 | 2.614 | |
| 15 | 6.609 | 13.309 | 8.838 | 13.632 | 6.979 | 13.684 | 7.416 | 12.700 | |
| 16 | 18.574 | 23.862 | 15.339 | 21.222 | 14.673 | 23.576 | 15.903 | 22.604 | |
| 17 | 3.165 | 8.787 | 6.139 | 8.644 | 5.548 | 9.233 | 5.311 | 8.130 | |
| 18 | 11.381 | 16.601 | 10.039 | 14.139 | 9.902 | 16.849 | 9.865 | 14.593 | |
| 19 | -4.587 | 1.845 | 2.106 | 3.945 | 2.253 | 3.046 | 2.471 | 3.389 | |
| 20 | 11.684 | 19.085 | 9.137 | 15.776 | 9.186 | 19.255 | 9.685 | 17.159 | |
| 21 | 30.767 | 39.591 | 20.246 | 34.593 | 16.796 | 41.072 | 20.369 | 40.407 | |
| 22 | 14.250 | 19.840 | 10.430 | 16.253 | 11.581 | 20.525 | 11.374 | 18.048 | |
| 23 | -1.579 | 5.613 | 3.900 | 6.687 | 4.071 | 7.662 | 3.909 | 6.214 | |
| 24 | 7.648 | 15.276 | 7.099 | 11.493 | 7.462 | 14.583 | 7.130 | 11.736 | |
| 25 | 16.199 | 28.828 | 13.006 | 22.695 | 10.971 | 34.746 | 12.089 | 28.318 | |
| 26 | -1.967 | 5.227 | 4.421 | 7.029 | 4.083 | 7.261 | 4.032 | 6.293 | |
| 27 | -9.730 | -1.580 | 1.360 | 2.712 | 2.092 | 2.281 | 2.040 | 2.436 | |
| 28 | 38.873 | 49.077 | 25.212 | 43.588 | 25.181 | 51.940 | 29.184 | 52.086 | |
| 29 | -2.236 | 4.142 | 2.947 | 4.616 | 3.177 | 5.048 | 2.995 | 4.262 | |
| 30 | 52.335 | 61.993 | 44.400 | 73.879 | 41.599 | 63.278 | 45.867 | 65.148 | |
| 31 | 2.314 | 7.774 | 6.042 | 8.344 | 5.463 | 8.784 | 5.225 | 7.856 | |
| 32 | 12.515 | 20.205 | 12.503 | 22.001 | 9.080 | 18.449 | 9.767 | 19.490 | |

Following [8], multivariate kurtosis  is estimated for the data from Table 1 and the normalized data on the basis of the Johnson univariate and multivariate transformations for  family. It is known that  holds under multivariate normality. In our case . The estimators of multivariate kurtosis equal 28.66, 23.87, 37.29 and 23.08 for the data from Table 1, the normalized data on the basis of the decimal logarithm transformation, the Johnson univariate and multivariate transformations respectively. The values of these estimators indicate that the assumption of multivariate normality for the data from Table 1 and for the data from Table 1 normalized by the Johnson univariate transformation of  family is rejected.

Squared MD is used for checking multivariate normality (MVN). According MD MVN test, the assumption of multivariate normality for the data from Table 1 normalized by the Johnson multivariate transformation (5.1) of  family and the decimal logarithm transformation is not rejected for 0.005 significance level. The assumption of multivariate normality for the data from Table 1 and for the data from Table 1 normalized by the Johnson univariate transformation of  family is rejected for 0.005 significance level.

It should be noted that the poor normalization of multivariate non-Gaussian data using the Johnson univariate transformation leads to an expansion of the confidence and prediction intervals of nonlinear regression for a larger number of data rows compared to both the Johnson multivariate transformation and the decimal logarithm transformation. The values of  and MMRE are better for the equation (5.4) for the Johnson multivariate transformation in comparison with all previous regression equations, both linear and nonlinear, based on univariate transformations. This can be explained best by the multivariate normalization and the fact that there is no reason to reject the hypothesis that the sample of data, which normalized by the Johnson multivariate transformation for  family, comes from a multivariate normal distribution.

6 Conclusions

To sum it up, when constructing the equations, confidence and prediction intervals of nonlinear regressions for multivariate non-Gaussian data multivariate normalizing transformations should be used.

From the examples we can make a conclusion that the considered techniques based on multivariate normalizing transformations are promising ones, since they lead to a narrowing of the confidence and prediction intervals of nonlinear regression for a larger number of data rows compared to the univariate normalizing transformations.

As a rule, poor normalization of multivariate non-Gaussian data using univariate transformations instead of multivariate ones can result in an expansion of the confidence and prediction intervals of nonlinear regression.

Prospects for the further research include the application of new multivariate normalizing transformations and data sets for constructing the equations, confidence and prediction intervals of nonlinear regressions for multivariate non-Gaussian data.

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