Using the classical linear regression model in analysis of the dependences of conveyor belt life

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The paper deals with the classical linear regression model of the dependence of conveyor belt life on some selected parameters: thickness of paint layer, width and length of the belt, conveyor speed and quantity of transported material. The first part of the article is about regression model design, point and interval estimation of parameters, verification of statistical significance of the model, and about the parameters of the proposed regression model. The second part of the article deals with identification of influential and extreme values that can have an impact on estimation of regression model parameters. The third part focuses on assumptions of the classical regression model, i.e. on verification of independence assumptions, normality and homoscedasticity of residuals.

Key words: *conveyor belt, regression model, residuals, random model component, influential and extreme values*

Introduction

Belt transport belongs to continuous transport systems characterised by great performance and capacity. Belt conveyors are used to transport different material in many industries, such as mechanical engineering, metallurgy, mining, building etc. One of the main parts of a belt conveyor is the conveyor belt, which is made from flexible parts able to transmit axial forces of longitudinal and transverse bending.

The conveyor belt is the most important part of belt conveyors. At the operation, it is exposed to high stress, abrasion, wear, bad meteorological conditions, heat, chemical substances. It serves for driving the belt conveyor and it moves together with the load by looping around the drive pulley and idler after its endings are laterally joined. The belt is driven by table rolls and consists of the upper driving line and of the bottom reverse layer [8, 9].

Our paper will deal with the linear regression model to determine dependence of the conveyor belt life based on some parameters got from the operation logbook at the quarry Včeláre (Tab. 1), where there are over 30 belt conveyors, including the mobile ones used mainly for finishing. We will take into consideration only the conveyor belts the operation life of which we were able to detect.

The service life of conveyor belts is the main parameter of economical effectiveness of belt transport. Many factors have a direct or indirect impact on the life of conveyor belts. The optimal life L of conveyor belts was calculated according to the relation $L=\sqrt{\frac{2(c_z-c_v)}{c_r}}$, where c_z is the cost of acquisition, c_v is the residual cost of the conveyor belt and c_r are increasing maintenance costs [10, 11, 12].

Regression model, estimation of the parameters and verification of the regression model

We will examine the dependence of the life of 18 conveyor belts on some parameters: thickness of paint layer, width and length of the conveyor, speed and the quantity of transported material per 1 m^2. Basic descriptive statistics are in the Tab. 1.

The linear regression model, which characterizes dependence of the optimal life of the belt Z (dependent variable) on independent (explanatory) variables (thickness of the paint layer of the conveyor belt t, its width w, its length l, its speed s, transported quantity of material q) is the following [1]

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Tab. 1. Simple descriptive statistics.

Variable	Count	Mean	Std dev	Sum	Minimum	Maximum
Thickness of paint t **(mm)**	18	7,500	1,505	135,0	6,0	12,0
Width w **(m)**	18	1,056	0,192	19,0	0,8	1,4
Length l **(m)**	18	65,222	64,147	13558,9	7,0	196,0
Speed s **(m/s)**	18	1,489	0,128	26,8	1,4	1,8
Quantity of transported q **per t/hm^2**	18	6,240	7,434	112,3	0,4	25,7
Life L **(month)**	18	19,211	10,441	345,8	8,4	40,4

$$\hat{y}_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \beta_3 x_{i3} + \beta_4 x_{i4} + \beta_5 x_{i5} + \varepsilon_i \text{, or}$$

$$\hat{y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \varepsilon \ , \qquad (1)$$

where $x_1 = t, x_2 = w, x_3 = l, x_4 = s, x_5 = q$ and $\hat{y} = L$.

Generally, the point estimation for the linear regression model is

$$\hat{y}_i = b_0 + b_1 x_{i1} + b_2 x_{i2} + b_3 x_{i3} + b_4 x_{i4} + b_5 x_{i5k} \ ,$$

where $\hat{y}_i$ is fitted (theoretical) value of the dependent variable, b_0 is estimation of the intercept and b_j, $j = 1,\ldots,5$ is the partial coefficient that is the point estimation of the regression coefficient. The point estimation of the model of the conveyor belt is

$$\hat{y}_i = 22{,}5278 - 0{,}2522 x_{i1} + 4{,}9979 x_{i2} - 0{,}0673 x_{i3} - 5{,}5522 x_{i4} + 0{,}9470 x_{i5} \ . \qquad (2)$$

The constant $b_0 = 22{,}5278$ represents the average conveyor belt life. Points estimation and confidence intervals for each regression model coefficients are shown in Table 2.

Tab. 2. Points estimation and confidence intervals.

Coefficient	Points estimation	90 % interval		95 % interval	
		Lower limit	Upper limit	Lower limit	Upper limit
b_0	22,5278	–2,9655	48,0211	–8,6372	53,6929
b_1 (t)	–0,2522	–2,0613	1,5569	–2,4638	1,9594
b_2 (w)	4,9979	–7,2178	17,2135	–9,9356	19,9313
b_3 (l)	–0,0673	–0,1097	–0,0248	–0,1192	–0,0154
b_4 (s)	–5,5522	–21,4327	10,3877	–24,9724	13,9274
b_5 (q)	0,9470	0,5866	1,3054	0,5089	1,3851

The graph of fitted (theoretical) life values $\hat{y}_i$ versus residuals between empirical values and fitted values is presented in Fig.1.

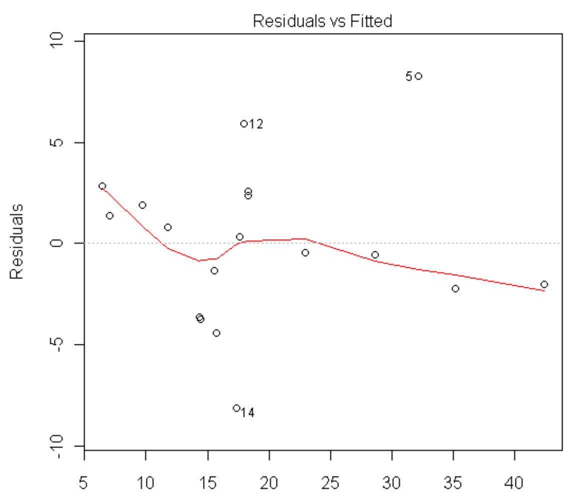

Fig. 1. Graph of fitted life values vs. residuals.

The interval estimation of the model parameters can be used for statistical testing to define significance of the model parameters. In case the zero lies in the given interval of parameter reliability, then the given parameter is statistically insignificant (in our case almost all coefficients, except b_3 and b_5, seem to be statistically insignificant).

By using **F-test of the statistical significance of the model**, we will verify to what extent the linear regression model estimated via the method of least squares defines the variability of the dependent variable, and we will see if the influence of an explanatory variable on an explained variable (conveyor belt life) is relevant or not. We test the hypotheses: H_0 :regression model is not statistically significant, (all regression coefficients are zero) versus H_1 : regression model is statistically significant, (at least one regression coefficient is not zero). In the Tab. 3 there is the final variance analysis for the proposed regression model.

Tab. 3. Analysis of Variance.

Variability	**Sum of squares**	**Degrees of freedom**	**Average square**	**Test characteristic F**
Explained by the model	$SS_M = 1598{,}769$	$df_M = 5$	$MS_M = 319{,}7538$	$F = \frac{MS_M}{MS_R} = 15{,}08$
Residual	$SS_R = 254{,}4489$	$df_R = 2$	$MS_R = 21{,}2041$	
Total	$SS_T = 1853{,}218$	$df_T = 17$		

The value of the test characteristic is $F = 15{,}08$, the critical value $F_{0,95}(5;12) = 3{,}106$. Since $F = 15{,}08 > F_{0,95}(5;12) = 3{,}106$ (p-value$= 8{,}14.10^{-6} < \alpha$), we reject the null hypothesis at the significance level $\alpha = 0{,}05$ and we can assume that the proposed regression model is statistically significant; and at least one of the explanatory variables has a considerable impact on the conveyor belt life. The quotient $\frac{SS_M}{SS_T}.100\% = 86{,}27\%$ represents the variability of the life variable L explained by this model.

The statistical significance of individual parameters will be verified by means of the **t-test of the statistical significance of the regression coefficient** β_j. We test H_0 :regression coefficient is not statistically significant, or ($\beta_j = 0$) versus H_1 : regression coefficient is statistically significant, or ($\beta_j \neq 0$).

We reject the null hypothesis at the significance level only in two cases (p-value <α) – the parameters of conveyor belt length l and of transported quantity of material q. We do not reject the null hypothesis in the other cases, and the explanatory variables conveyor width w, thickness of paint layer t and conveyor speed s can be excluded from this model.

In the Tab. 4 there are parameter estimations, interval estimations of the parameters and assessment of explanatory variables contribution to the proposed model.

Tab. 4. Parameter estimations and t-test.

Parameter	**Point estimation**	**t**	**p-value**	**95 % interval**	
				Lower Limit	**Upper Limit**
b_0	22,5278	1,575	0,1412	–8,6372	53,6929
b_1 (t)	–0,2522	–0,248	0,8080	–2,4638	1,9594
b_2 (w)	4,9979	0,729	0,4799	–9,9356	19,9313
b_3 (l)	–0,0673	–2,825	0,0153 *	–0,1192	–0,0154
b_4 (s)	–5,5522	–0,619	0,5477	–24,9724	13,9274
b_5 (q)	0,9470	4,710	0,00045 *	0,5089	1,3851

The point estimation of the multiple correlation coefficient ρ is the sample multiple correlation coefficient $r = 0{,}9288$. The adjusted (rectified) coefficient of the determination $r_{adj} = 0{,}8975$ is so called undisturbed estimation of the multiple correlation coefficient of the determination; it takes into consideration the number of explanatory parameters of the model.

We test the statistical significance of multiple correlation coefficient by performing test. The null hypothesis is $H_0 : \rho = 0$ against alternative hypothesis $H_1 : \rho \neq 0$. Since value of test statistic is $F = 15 > F_{0,95}(5;\,12) = 3{,}106$, the null hypothesis can be rejected and it can be assumed, that on significance level $\alpha = 0{,}05$ between described variable and explanatory variables is statistically significant linear dependency.

Identification of the influential and outlying values

The identification of the influential values is not a simple or an unambiguous matter. In order to diagnose influential observations and to verify assumptions about the random component of the regression model, the projection matrix H (hat matrix) and different types of residuals are used [13].

The diagonal elements h_{ii} of the hat matrix are called project elements h, or influence, effect (leverage) and they assess the influence of observation i on the values of estimated parameters. They get the values $0 \leq h_{ii} \leq 1$ (or $\frac{1}{n} \leq h_{ii} \leq 1$) and their sum is $\sum_{i=1}^{n} h_{ii} = k + 1 = p$. The average value of the diagonal element is $\overline{h}_{ii} = \frac{p}{n}$, where p is the number of estimated parameters of the model and n is the number of observations.

The observation, where the element $h_{ii} > \frac{2p}{n}$ is considered as extreme observation [13]. An extreme observation may not be influential; on the contrary an observation with a small element h_{ii} can influence the estimation of the regression model parameters.

To assess the quality of the regression model, the residuals are used [10]. We will use classical residuals $e_i = y_i - \widehat{y}_i$, where y_i are empirical values and $\widehat{y}_i$ fitted (theoretical) values, predicated residuals $e_{i(-i)} = \frac{e_i}{1 - h_{ii}}$, studentized residuals $e_{Si} = \frac{e_i}{s_{rez} \cdot \sqrt{1 - h_{ii}}}$ and jackknife residuals $e_{Ji} = \frac{e_i}{s_{rez(-i)} \cdot \sqrt{1 - h_{ii}}}$, where s_{rez} is the residual standard deviation belonging to the regression model based on n observations, and $s_{rez(-i)}$ is the standard residual deviation belonging to the regression model based on $n-1$ observations.

There are several ways (statistics) how to **identify influential points** [13]:

- $PRESS = \sum_{i=1}^{n} e_{i(-i)}^2$, if the quotient $q = \frac{\sum_{i=1}^{n} e_{i(-i)}^2}{\sum_{i=1}^{n} e_i^2}$ is much higher than 1, it indicates influential observations,
- $DFFIT_{(-i)} = \sqrt{\frac{h_{ii}}{1 - h_{ii}}} \cdot e_{Ji}$, where observation i is considered as influential, if $\left| DFFIT_{(-i)} \right| > 2 \cdot \sqrt{\frac{p}{n}}$,
- cook distance $D_i = \frac{e_{S_i}^2 \cdot h_{ii}}{p \cdot (1 - h_{ii})}$, if $D_i > \frac{4}{n}$, then observation i is outlying; better said, the observation for which, $D_i \geq F_{0,5}(p, n - p)$,
- Andrews-Pregibon distance $AP_i = (1 - h_{ii}) \cdot \left(1 - \frac{e_i^2}{n - p} \right)$, where observation i being truly influential if $AP_i \leq 1 - \frac{2(p + 1)}{n}$,
- $COVRATIO_{(-i)} = \left[\frac{s_{rez(-i)}}{s_{rez}} \right]^p \cdot \frac{1}{1 - h_{ii}}$, where the observation i is considered as influential if $\left| COVRATIO_{(-i)} - 1 \right| > \frac{3p}{n}$.

The residuals together with other statistics are shown in the Tab. 5. The sum $PRESS = \sum_{i=1}^{n} e_{i(-i)}^2 = 492{,}613$ is considerably different from the sum $\sum_{i=1}^{n} e_i^2 = 254{,}3883$ and their quotient $q = 1{,}9365$ is much higher than 1, this is why there are influential observations in the data set. The 4th, 14th and 16th observations are the most influential, because their differences between the classical and predicated residuals are the highest.

Tab. 5. Residuals, extreme and influential values.

No.	**L**	**L***	**e_i**	**e_{Si}**	**$e_{i(-i)}$**	**h_{ii}**	**DFFIT**	**D_i**	**AP_i**	**|COVRATIO$_i$-1|**
1	11,3	15,703	–4,403	–1,033	–5,108	0,138	–0,4137	0,0284	0,7912	0,122
2	10,7	4,353	–3,653	–0,852	–4,313	0,153	–0,3614	0,0223	0,7997	0,356
3	10,7	14,432	–3,732	–0,889	–4,574	0,184	–0,4221	0,0302	0,7664	0,362
4	40,4	42,404	–2,004	–0,634	–4,473	**0,552**	–0,7048	0,0871	0,4341	**2,036**
5	40,4	32,112	8,288	2,321	10,095	0,179	1,0830	0,1432	0,4808	0,812
6	20,7	18,323	2,377	0,552	2,885	0,176	0,2552	0,0115	0,8047	0,736
7	18	17,653	0,237	0,086	0,336	0,294	0,0555	0,0006	0,7056	**1,379**
8	22,5	22,947	–0,447	–0,135	–0,937	**0,523**	–0,1411	0,0036	0,4763	**2,501**
9	28,1	28,636	–0,536	–0,211	–1,921	**0,721**	–0,3401	0,0209	**0,2780**	**4,970**
10	32,9	35,117	–2,217	–0,629	-3,980	**0,443**	–0,5612	0,0552	0,5400	**1,450**
11	20,9	18,304	2,596	0,641	3,527	0,264	0,3843	0,0256	0,7127	0,839
12	23,9	17,992	5,908	1,582	7984	0,260	0,9364	0,1300	0,5975	0,334
13	11,6	9,718	1,882	0,449	2,438	0,228	0,2441	0,0106	0,7600	0,957
14	9,2	17,329	–8,129	–2,653	–12,224	0,335	**–1,8814**	**0,3924**	**0,3050**	0,870
15	12,6	11,77	0,83	0,197	1,082	0,233	0,1089	0,0021	0,7647	**1,152**
16	9,3	6,438	2,862	0,87	5,724	**0,500**	0,8706	0,1289	0,4709	**1,262**
17	8,4	7,012	1,388	0,374	2,306	0,398	0,3047	0,0167	0,5955	**1,597**
18	14,2	15,557	–1,357	–0,372	–2,332	0,418	–0,3152	0,0178	0,5758	**1,686**

Note: L are fitted values of belt conveyors life based on the regression model*

The diagonal elements of the hat matrix are in the Tab. 5. The results show that 5 observations seem to be extreme ($h_{ii} > 0{,}429$). According to used statistics, in the set there are several influential observations ($\left|DFFIT_{(-i)}\right| > 1{,}1547$, $D_i > 0{,}2222$, $AP_i \le 0{,}2222$, $\left|COVRATIO_{(-i)} - 1\right| > 1$).

Analysis of the random component of the regression model

For the regression model, we suppose that the random errors ε_i are interdependent with normal distribution with zero mean value and with constant variance σ_ε^2. The properties of random errors are: $E(\varepsilon_i) = 0$ (mean value of random errors ε_i is zero), $D(\varepsilon_i) = \sigma_\varepsilon^2$ (variance of random component ε_i is constant, errors homoscedasticity), $\mathrm{cov}(\varepsilon_i; \varepsilon_j) = 0$ for $i \ne j$ (mutual linear independence of random errors) and $\varepsilon_i \approx N(0; \sigma_\varepsilon^2)$, that means that random components ε_i have normal variance. If the proposed regression model is appropriate, then the classical residuals e_i should correspond to the properties of random errors ε_i.

The graphical analysis of the residuals has been carried out through the diagrams of studentized residuals e_{Si} with respect to the values of regression function $\hat{y}_i$, it means the point diagram $[\hat{y}_i; e_{Si}]$. According to [13], if the residuals belong to the horizontal zone around zero, and in the interval $(-2; 2)$ there are almost all studentized residuals, and out of the interval $(-3; 3)$ the residuals appear only sporadically (under 1 %), then the placement of the residuals does not indicate the violation of assumptions about random component.

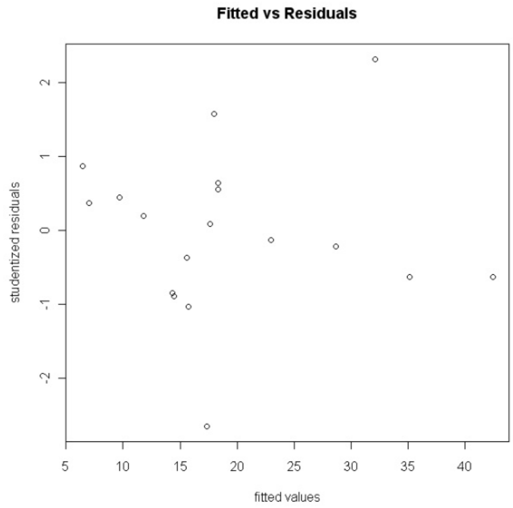

Fig. 2. Fitted values vs. studentized residuals.

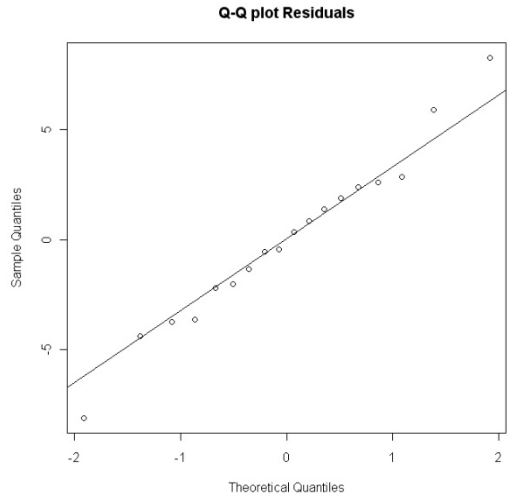

Fig. 3. Q-Q plot.

The studentized residuals are concentrated around 0, and the more distant they are from 0, the more their frequencies decrease (Fig. 2). In the interval $(-2; 2)$ there are over 95 % of the values, so the diagram does not indicate the violation of assumptions about random errors.

To verify the normality we use the graphical analysis based on so called diagnostic diagrams, i.e. we can use the Q-Q plot (Fig. 3), and also normality tests based on selected statistical tests (for example, Shapiro-Wilk, Pearson, Cramer von Mises tests etc.). We test H_0 : residuals are from normal distribution versus H_1 : residuals are not from normal distribution. The test characteristic of Shapiro-Wilk test W is equal to 0,9664, two-sided test p-value is 0,7278. Since p-value ≥ α, we do not reject the null hypothesis H_0 at the significance level $\alpha = 0{,}05$ (or $\alpha = 0{,}01$) and we can assume that the distribution of random errors is normal. We have obtained the same result when using Cramér-von Mises test (p-value is 0,93116) and Anderson-Darling normality test (p-value is 0,9046).

To verify **the assumption about constant variance** of random errors we will employ Goldfeld-Quandt test [13]. We test H_0 : homoscedasticity of residuals versus H_1 : heteroscedasticity of residuals. The set of balanced values is ascending and divided into 2 parts, where the sum of squares of studentized residuals squares is calculated. The value of the test characteristic is $F = 1{,}1503$. We reject the null hypothesis about homoscedasticity if $F > F_{1-\alpha}(n_2 - k - 1; n_1 - k - 1)$. Since $F = 1{,}1503 < F_{0{,}95}(3;3) = 9{,}277$, at the significance level $\alpha = 0{,}05$ we do not reject the null hypothesis about the constant variance of random errors. The homoscedasticity of residuals was verified also by Breusch-Pagan test, according to which, like in the previous test, we cannot reject the null hypothesis about constant variance of random errors (p-value is 0,5286).

Independence of random errors is verified through the coefficient of the 1st degree autocorrelation ρ_1 and by means of the most frequently employed autocorrelation Durbin-Watson test characteristic. We use the residuals arranged according to the size of regression function, and we will use both, classical e_i and studentized residuals e_{Si} .

The point estimation of the coefficient of the 1st degree autocorrelation is the selective autocorrelation coefficient for which is valid $r_1 = 0{,}1789$ (classical residuals), or $r_{1S} = 0{,}1067$ (studentized residuals).

The test of statistical significance of the 1st degree autocorrelation serves to test the independence of random errors. We test H_0 : $\rho_1 = 0$ versus $H_1 : \rho_1 \neq 0$ (or H_0 : autocorrelation coefficient is not statistically significant; errors are mutually independent versus H_1 : autocorrelation coefficient is statistically significant; error are interdependent, autocorrelated).

We reject the null hypothesis at the significance level α , if $|r_1| \geq |r_\alpha(n)|$, where $r_\alpha(n)$ is tabular critical value. Because the studentized residuals $|0{,}1789| < |r_{0{,}05}(18)| = 0{,}299$ (or $|0{,}1067| < |r_{0{,}05}(18)| = 0{,}299$). At the significance level $\alpha = 0{,}01$ is $r_{0{,}01}(18) = 0{,}432$. The result of the test shows that the 1st degree autocorrelation coefficient is not statistically significant and the assumption about the independence of errors can be considered as satisfied.

Durbin-Watson test characteristic for classical residuals is $D-W=1{,}559$, or $D-W=1{,}7275$ for studentized residuals. Generally, the values $D-W$ are from the interval $\langle 0,4 \rangle$. In practice, we can follow the simplified rule saying that the value of the test characteristic $D-W$ close to 2 indicates the independence of random errors. According to [7], if the test characteristic value lies in the interval (1,4; 2,6), the residuals do not show the autocorrelation.

Conclusion

Our paper describes the analysis of the classical regression model of the dependence of conveyor belt life on some parameters. Next possibility is to describe dependency of models, which are defined in articles [2, 3, 4, 5, 6, 8].

We employed the test of statistical significance of the regression model to verify if the proposed regression model is statistically significant. The model analysis shows that, thanks to the proposed model, we are able to explain the variability of the life variable L by means of selected parameters up 86,27 %. 13,73 % left are caused by the factors that are not included in this model, or by other explanatory variables, or random influences.

Thanks to the test of statistical significance of the regression coefficient, we found out that the explanatory variables conveyor belt length l and transported quantity q are statistically significant and have a considerable impact on the conveyor belt life. The test results also show that the other parameters, such as conveyor belt width w, thickness of paint layer t and conveyor belt speed s can be excluded from the proposed regression model. The point estimation of the new linear model of the conveyor belt is $\hat{y}_i = 17{,}9089 - 0{,}069 x_{1i} + 0{,}9301 x_{2i}$, where $x_1 = l, x_2 = q$. The new point estimation of the multiple correlation coefficient is 0,9238 and the adjusted coefficient of the determination is 0,9132. The explanation of the variability of the life variable L by means of two selected parameters is 85,3 %.

The following part dealt with influential observations and assumptions of the classical linear regression model. The results of the random errors analysis of the proposed model confirm assumptions of normality and homoscedasticity of random errors. According to Durbin-Watson characteristic and autocorrelation coefficient we cannot reject the hypothesis about independence of random errors.

The results of identification and diagnosis of extreme and influential values show that among the observed values there are several extreme and influential values that concern the regression model and that these can have a considerable impact on the model parameters and characteristics. Their omission in the model can considerably modify the estimations of the model parameters. It is important to realise that some errors might have occurred while measuring or collecting data or they may result from an incorrect design of the regression model or they are due to the combination of explanatory variables.

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