UDK 621.9.025.5:669.14
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
MTAEC9, 45(2)105(2011)

MULTI-OBJECTIVE OPTIMIZATION OF THE CUTTING FORCES IN TURNING OPERATIONS USING THE GREY-BASED TAGUCHI METHOD

MULTI NAMENSKA OPTIMIZACIJA STRUŽENJA Z UPORABO TAGUCHI METODE NA GREY PODLAGI

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Prejem rokopisa – received: 2010-06-18; sprejem za objavo – accepted for publication: 2011-02-02

This study investigated the multi-response optimization of the turning process for an optimal parametric combination to yield the minimum cutting forces and surface roughness with the maximum material-removal rate (MRR) using a combination of a Grey relational analysis (GRA) and the Taguchi method. Nine experimental runs based on an orthogonal array of the Taguchi method were performed to derive objective functions to be optimized within the experimental domain. The objective functions were selected in relation to the parameters of the cutting process: cutting force, surface roughness and MRR. The Taguchi approach was followed by the Grey relational analysis to solve the multi-response optimization problem. The significance of the factors on the overall quality characteristics of the cutting process was also evaluated quantitatively using the analysis-of-variance method (ANOVA). Optimal results were verified through additional experiments. This shows that a proper selection of the cutting parameters produces a high material-removal rate with a better surface roughness and a lower cutting force.

Keywords: turning, cutting, Grey relation analysis, Taguchi method, optimization

Raziskani so odgovori optimizacije procesa struženja z optimalno kombinacijo parametrov s ciljem doseči minimalne sile rezanja in hrapavost površine pri maksimalni odstranitvi materiala (MRR) z uporabo kombinacije Grey odvisnostne analize (GRA) in Taguchi metode. Devet preizkusov na podlagi ortogonalne ureditve po Taguchi metodi je bilo izvršeno za razvoj objektivnih funkcij in njihovo optimizacijo v področju preizkusov. Objektivne funkcije so bile izbrane glede na proces rezanja: sila rezanja, hrapavost površine in MRR. Taguchi približek z Grey analizo odvisnosti je bil uporabljen za rešitev problema optimizacije z več odgovori. Pomen dejavnikov na kakovostne značilnosti procesa rezanja je bil kvantitativno ocenjen z uporabo metode analize variance (ANOVA). Optimalni rezultati so bili verificirani z dopolnilnimi preizkusi. Rezultati kažejo, da prava izbira parametrov rezanja zagotovi visoko hitrost odstranjevanja materiala pri boljši kakovosti površine in manjši sili rezanja.

Ključne besede: struženje, rezkanje, Grey analiza, Taguchi metoda, optimizacija

1 INTRODUCTION

Turning is a very important machining process in which a single-point cutting tool removes material from the surface of a rotating cylindrical workpiece. The cutting tool is fed linearly in a direction parallel to the axis of rotation [1].

As indicated in **Figure 1**, the turning is carried out on a lathe that provides the power to turn the workpiece at a given rotational speed and to feed the cutting tool at a specified rate and depth of cut. Therefore, three cutting parameters, i.e., cutting speed (*V*), feed rate (*F*), and depth of cut (*d*), should be properly selected for a better surface finish with a lower cutting force.

In a turning operation, it is an important task to select the cutting parameters to achieve a high cutting performance. Usually, the desired cutting parameters are determined based on experience or by using a handbook [1]. However, this does not ensure that the selected cutting parameters have optimal or near optimal cutting performance for a particular machine and environment. To select the cutting parameters properly, several mathematical models [1–6] based on statistical regression techniques or neural computing have been constructed to establish

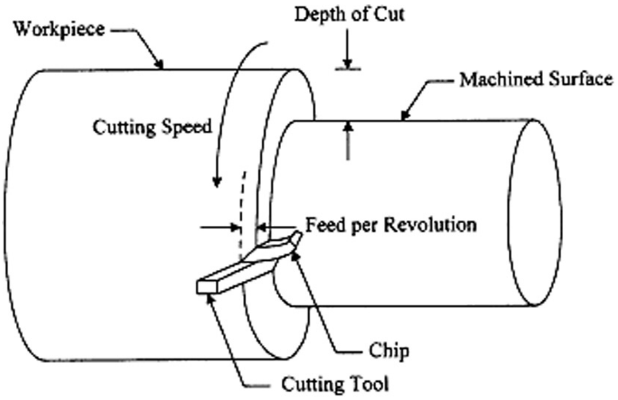

Figure 1: Schematic representation of the turning process [1]
Slika 1: Shema procesa struženja [1]

the relationship between the cutting performance and the cutting parameters. Then, an objective function with constraints is formulated to solve the optimal cutting parameters using optimization techniques. Therefore, considerable knowledge and experience are required to use this modern approach [1]. Furthermore, a large number of cutting experiments has to be performed and analyzed in order to build the mathematical models. Thus, the required model building is very costly in terms of time and materials [1].

Basically, the Taguchi method is a powerful tool for the design of high-quality systems. It provides a simple, efficient and systematic approach to optimize the designs for performance, quality, and cost [1–6]. The methodology is valuable when the design parameters are qualitative and discrete. Taguchi parameter design can optimize the performance characteristics through the settings of the design parameters and reduce the sensitivity of the system performance to sources of variation. In recent years, the rapid growth of interest in the Taguchi method has led to numerous applications of the method in a world-wide range of industries and countries [1,7,8].

Therefore, this study applied a Taguchi L_9 orthogonal array to plan the experiments on the turning process. The three controlling factors, including the cutting speed (V), the depth of cut (d) and feed rate (f), were selected. The Grey relational analysis is then applied to examine how the cutting factors influence the cutting force (F), the surface roughness (Ra) and the material removal rate (MRR). An optimal parameter combination was then obtained. Through analyzing the Grey relational grade matrix, the most influential factors for individual quality targets of the turning process can be identified. Additionally, an analysis of variance (ANOVA) was also utilized to examine the most significant factors for the F, Ra and MRR in the turning process.

2 GREY RELATIONAL ANALYSIS (GRA)

2.1 Data Preprocessing

In a Grey relational analysis, experimental data, i.e., measured features of the quality characteristics, are first normalized, ranging from zero to one. This process is known as Grey relational generation. Next, based on normalized experimental data, the Grey relational coefficient is calculated to represent the correlation between the desired and the actual experimental data. Then overall Grey relational grade is determined by averaging the Grey relational coefficient corresponding to selected responses [9]. The overall performance characteristic of the multiple response process depends on the calculated Grey relational grade. This approach converts a multiple-response process-optimization problem into a single-response optimization situation with the objective function of the overall Grey relational grade. The optimal parametric combination is then evaluated, which would result in the highest Grey relational grade. The optimal factor setting for maximizing the overall Grey relational grade can be performed using the Taguchi method [9,10].

In Grey relational generation, the normalized F and Ra corresponding to the smaller-the-better (SB) criterion which can be expressed as:

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)} \tag{1}$$

MRR should follow the larger-the-better (LB) criterion, which can be expressed as:

$$x_j(k) = \frac{y_j(k) - \min y_j(k)}{\max y_j(k) - \min y_j(k)} \tag{2}$$

where $x_i(k)$ and $x_j(k)$ are the value after the Grey relational generation for the SB and LB criteria, respectively. Min $y_i(k)$ is the smallest value of $y_i(k)$ and for the k^{th} response, and max $y_i(k)$ is the largest value of $y_i(k)$ for the k^{th} response [9]. An ideal sequence is $x_0(k)$ (k=1, 2,…,m) for the responses. The definition of the Grey relational grade in the course of the Grey relational analysis is to reveal the degree of relation between the 9 sequences [$x_0(k)$ and $x_i(k)$, k = 1,2,…,m and i = 1,2,…,9]. The Grey relational coefficient $\xi_i(k)$ can be calculated as:

$$\xi_i(k) = \frac{\Delta_{\min} - \psi\Delta_{\max}}{\Delta_{0i}(k) + \psi\Delta_{\max}} \tag{3}$$

where $\Delta_{0i} = \left\| x_0(k) - x_i(k) \right\|$ is the difference of the absolute value $x_0(k)$ and $x_i(k)$; ψ is the distinguishing coefficient $0 \le \psi \le 1$; $\Delta_{\min}(k) = \forall j^{\min} \in i \forall k^{\min} \left\| x_0(k) - x_j(k) \right\|$ is the smallest value of Δ_{0i}; and $\Delta_{\max}(k) = \forall j^{\max} \in i \forall k^{\max} \left\| x_0(k) - x_j(k) \right\|$ is the largest value of Δ_{0i}. After averaging the Grey relational coefficients, the Grey relational grade γ_i can be computed as:

$$\gamma_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k) \tag{4}$$

where n is the number of process responses. The higher value of the Grey relational grade corresponds to an intense relational degree between the reference sequence $x_0(k)$ and the given sequence $x_i(k)$. The reference sequence $x_0(k)$ represents the best process sequence; therefore, a higher Grey relational grade means that the corresponding parameter combination is closer to the optimal [9]. The mean response for the Grey relational grade with its grand mean and the main effect plot of the Grey relational grade are very important because the optimal process condition can be evaluated from this plot [9].

3 EXPERIMENTAL PROCEDURE AND TEST RESULTS

3.1 Experimental Details

The cutting experiments were carried out on an experimental lathe setup using a HSS cutting tool for the machining of the AISI 1050 steel bar, which is 30 mm in diameter and 80 mm in length. The mechanical properties and percent composition of the workpiece material is listed in **Table 1**.

A *Phynix TR-100* model surface-roughness tester was used to measure the surface roughness of the machined samples. The cut-off length (λ) was chosen as 0.3 for each roughness measurement. An average of six measurements of the surface roughness was taken to use in the multi-criteria optimization. Also, the MRR (mm^3/min) was calculated using Eq. (5);

$$MRR = 1000\ Vfd \tag{5}$$

where f/(mm/r) denotes the feed rate, d/mm describes the cutting depth and V/(m/min) represents the cutting speed of the turning operation.

3.2 Process Parameters and Test Results

In full factorial design, the number of experimental runs exponentially increases as the number of factors, as well as their level increases. This results in a huge experimentation cost and considerable time periods [9]. So, in order to compromise these two adverse factors and to search for the optimal process condition through a limited number of experimental runs Taguchi's L_9 orthogonal array consisting of 9 sets of data was selected to optimize the multiple performance characteristics of the turning process. Experiments were conducted with the process parameters given in **Table 2**, to obtain the machined surface on the AISI 1050 medium-carbon steel. The feasible space for the cutting parameters was defined by varying the cutting speed in the range 110–600 m/min, the feed rate in the range 0.2–0.6 mm/min, and the depth of cut in the range 0.5–1.5 mm.

The initial cutting parameters were selected as: cutting speed of 110 m/min; feed rate of 0.20 mm/min; and depth of cut of 0.5 mm. In the cutting parameter design, three levels of the cutting parameters were selected, as shown in **Table 2**. In order to prevent a sudden increase of the cutting forces due to the dullness of the cutting edge, the HSS tool was changed after three repetitions of each experiment.

Table 3 shows the selected design matrix based on the Taguchi L_9 orthogonal array consisting of 9 sets of coded conditions and the experimental results for the responses of *F*, *Ra* and MRR. All these data were utilized for the analysis and evaluation of the optimal parameter combination required to achieve the desired quality within the experimental domain.

4 PARAMETRIC OPTIMIZATION OF THE CUTTING PROCESS

4.1 Evaluation of the Optimal Process Condition

First, by using Eqs. (1) and (2), the experimental data were normalized to obtain the Grey relational generation [9]. The normalized data and $\Delta_{0i}(k)$ for each of the responses are listed in **Table 4** and **Table 5**, respectively. For MRR the *larger-the-better (LB)* and for F and Ra the *smaller-the-better (SB)* criteria were selected.

Table 3: Orthogonal array L_9 of the experimental runs and results
Tabela 3: Ortogonalna razporeditev L_9 eksperimentov in rezultati

Run no	Parameter level			Experimental results		
	V	f	d	MRR/(mm^3/min)	F/N	Ra/µm
1	1	1	1	0.11	123	0.87
2	1	2	2	0.44	179	2.33
3	1	3	3	0.99	364	6.62
4	2	1	2	0.60	166	1.98
5	2	2	3	1.80	295	3.82
6	2	3	1	0.90	255	3.96
7	3	1	3	1.80	340	0.92
8	3	2	1	1.20	218	1.22
9	3	3	2	3.60	268	5.60

Table 1: Chemical and mechanical properties of AISI 1050 medium carbon steel
Tabela 1: Kemična sestava in mehanske lastnosti jekla AISI 1050 s srednjim ogljikom

Chemical composition w/%	C	P	S	Mn	Cr	Fe	Ni	Cu
	0.49	0.02	0.02	0.78	0.08	97.99	0.10	0.26
Mechanical properties	Yield strength (MPa)		Tensile strength (MPa)		Elongation (%)		Vickers Hardness (HV)	
	365		636		24		261	

Table 2: Cutting parameters and their limits
Tabela 2: Parametri rezanja in njihove meje

Cutting Parameters	Notation	Unit	*Levels of factors*		
			1	2	3
Cutting speed	V	m/min	110*	300	600
Feed rate	f	mm/min	0.2*	0.4	0.6
Depth of cut	d	mm	0.5*	1.0	1.5

*Initial cutting parameter

Table 4: Grey relational generation of each performance characteristics
Tabela 4: Grey relacijska generacija vsake karakteristike performance

Run no	MRR	F	Ra
	Larger-the-better	Smaller-the-better	Smaller-the-better
Ideal sequence	1.000	1.000	1.000
1	0.000	1.000	1.000
2	0.095	0.768	0.746
3	0.252	0.000	0.000
4	0.140	0.822	0.807
5	0.484	0.286	0.487
6	0.226	0.452	0.463
7	0.484	0.100	0.991
8	0.312	0.606	0.939
9	1.000	0.398	0.177

Table 5: Evaluation of $\Delta_{0i}(k)$ for each of the responses
Tabela 5: Ocena $\Delta_{0i}(k)$ za vsak odgovor

Run no	*MRR*	*F*	*Ra*
Ideal sequence	1.000	1.000	1.000
1	1.000	0.000	0.000
2	0.905	0.232	0.254
3	0.748	1.000	1.000
4	0.860	0.178	0.193
5	0.516	0.714	0.513
6	0.774	0.548	0.537
7	0.516	0.900	0.009
8	0.688	0.394	0.061
9	0.000	0.602	0.823

Table 6 shows the calculated Grey relational coefficients (with the weights of $\psi_{\mathrm{MRR}} = 0.33$, $\psi_{\mathrm{F}} = 0.33$ and $\psi_{\mathrm{Ra}} = 0.33$) of each performance characteristic using Eq. (3).

Table 6: Grey relational coefficient of each performance characteristics ($\psi_{\mathrm{MRR}} = 0.33$, $\psi_{\mathrm{F}} = 0.33$ and $\psi_{\mathrm{Ra}} = 0.33$)
Tabela 6: Grey odvisnostni koeficient za vsako značilnost performance ($\psi_{\mathrm{MRR}} = 0.33$, $\psi_{\mathrm{F}} = 0.33$ and $\psi_{\mathrm{Ra}} = 0.33$)

Run no	*MRR*	*F*	*Ra*
Ideal sequence	1.000	1.000	1.000
1	0.248	1.000	1.000
2	0.267	0.587	0.565
3	0.306	0.248	0.248
4	0.277	0.649	0.631
5	0.390	0.316	0.391
6	0.299	0.376	0.380
7	0.390	0.268	0.974
8	0.324	0.456	0.844
9	1.000	0.354	0.286

The Grey relational coefficients, given in **Table 7**, for each response have been accumulated by using Eq. (4) to evaluate the Grey relational grade, which is the overall representative of all the features of the cutting-process quality. Thus, the multi-criteria optimization problem has been transformed into a single equivalent objective function optimization problem using a combination of the Taguchi approach and Grey relational analyses. The higher is the value of the Grey relational grade, the corresponding factor combination is said to be close to the optimal [9].

Table 7: Grey relational grade
Tabela 7: Grey stopnja odvisnosti

Run no	Grey relational grade	Rank
1	0.7119	1
2	0.4683	6
3	0.2648	9
4	0.5139	5
5	0.3623	7
6	0.3483	8
7	0.5388	3
8	0.5360	4
9	0.5414	2

The signal-to-noise (*S/N*) ratio is a measure of the magnitude of a data set relative to the standard deviation. If the S/N is large, the magnitude of the signal is large relative the noise, as measured with the standard deviation [11]. Table 8 shows the *S/N* ratio based on the *larger-the-better* criterion for the overall Grey relational grade calculated using Eq. (6).

$$S/N = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \qquad (6)$$

where n is the number of measurements, and y_i is the measured characteristic value.

Table 8: *S/N* ratio for overall Grey relational grade
Tabela 8: *S/N* razmerje za splošno Grey stopnjo

Run no	S/N
1	–2.59
2	–6.59
3	–11.54
4	–5.78
5	–8.82
6	–9.16
7	–5.37
8	–5.42
9	–5.33

Table 9: Response Table for the mean Grey relational grade
Tabela 9: Tabela odgovorov za povprečno Grey stopnjo odvisnosti

Factors	*Grey relational grade*			
	Level 1	*Level 2*	*Level 3*	*max-min*
V	0.49	0.41	0.54	0.13
f	0.60	0.46	0.38	0.22
d	0.54	0.51	0.39	0.15

Total mean Grey relational grade = 0.48

A graphical representation of the *S/N* ratio for the overall Grey relational grade is shown in **Figure 2**. The dashed line is the value of the total mean of the *S/N* ratio.

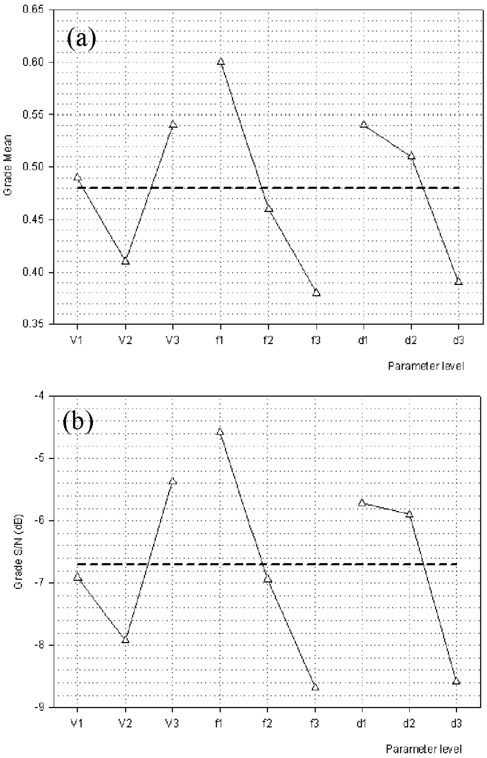

Figure 2: (a) Mean plot, (b) *S/N* plot for the Grey relational grade
Slika 2: (a) Povprečna odvisnost, (b) *S/N* odvisnost za Grey stopnjo odvisnosti

As indicated in **Figure 2**, the optimal condition for the turning of the AISI 1050 medium-carbon steel becomes $V_3 f_1 d_1$. **Table 9** shows the mean Grey relational grade ratio for each level of the process parameters.

4.2 Analysis of Variance (ANOVA)

The purpose of the analysis of variance (ANOVA) is to investigate which turning parameters significantly affect the performance characteristics [8–10]. This is accomplished by separating the total variability of the grey relational grades, which is measured by the sum of the squared deviations from the total mean of the grey relational grade, into contributions from each of the turning parameters and the error [9]. Thus;

$$SS_{\mathrm{T}} = SS_{\mathrm{F}} + SS_{\mathrm{e}} \tag{7}$$

where

$$SS_{\mathrm{T}} = \sum_{j=1}^{p} (\gamma_j - \gamma_m)^2 \tag{8}$$

SS_T – Total sum of the squared deviations about the mean
γ_j – Mean response for the j^{th} experiment
γ_m – Grand mean of the response
p – Number of experiments in the orthogonal array
SS_F – Sum of the squared deviations due to each factor
SS_e – Sum of the squared deviations due to error

In addition, the *F* test was used to determine which turning parameters have a significant effect on the performance characteristic. Usually, the change of the turning parameter has a significant effect on the performance characteristics when the *F* value is large [8–10]. The ANOVA for the overall Grey relational grade is shown in **Table 10**.

Table 10: ANOVA results of turning process parameters
Tabela 10: ANOVA rezultati parametrov procesa struženja

Parameter	Degree of Freedom	Sum of Square	Mean Square	*F*	Contribution (%)
V	2	0.026	0.013	1.21	17.81
f	2	0.071	0.035	3.27	48.63
d	2	0.039	0.019	1.79	26.71
Error	2	0.010	0.011		6.85
Total	8	0.158			100

According to this analysis, the most effective parameters with respect to the material-removal rate, the cutting force and the surface roughness are the feed rate, the depth of cut and the cutting speed. The percentage contribution indicates the relative power of a factor to reduce the variation. For a factor with a high percentage contribution, there is a great influence on the performance. The percent contributions of the cutting parameters on the material-removal rate, the cutting force and the surface roughness are shown in Table 10 and **Figure 3**. The feed rate was found to be the major factor affecting the material-removal rate, the cutting force and the surface roughness (48.63 %), whereas the depth of cut (26.71 %) and the cutting speed (17.81 %) were found to be the second- and third-ranking factors respectively.

4.3 Confirmation Test

After evaluating the optimal parameter settings, the next step is to predict and verify the enhancement of the quality characteristics using the optimal parametric combination [9]. The estimated Grey relational grade $\hat{\gamma}$ using the optimal level of the design parameters can be calculated as:

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{o} (\bar{\gamma}_j - \gamma_m) \tag{9}$$

where γ_m is the total mean Grey relational grade, $\bar{\gamma}_i$ is the mean Grey relational grade at the optimal level, and

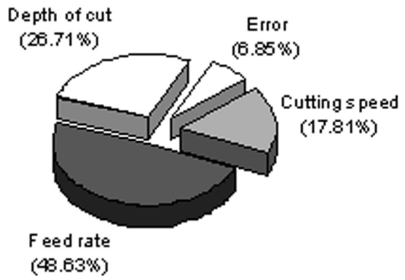

Figure 3: Contribution percentage of the cutting parameters
Slika 3: Prispevni procent parametrov rezanja

Table 11: Results of confirmation test
Tabela 11: Rezultati potrditvenega preizkusa

	Initial factor settings	Optimal process condition	
		Prediction	Experiment
Factor levels	$V_1 f_1 d_1$	$V_3 f_1 d_1$	$V_3 f_1 d_1$
$MRR/(mm^3/min)$	0.11		0.30
F/N	123		115
$Ra/\mu m$	0.87		0.65
S/N ratio of overall Grey relational grade	–2.59	–2.21	-–2.18
Overall Grey relational grade	0.71	0.72	0.77

Improvement in Grey relational grade = 0.06

o is the number of the main design parameters that affect the quality characteristics [9]. **Table 11** indicates the comparison of the predicted tensile strength and elongation with that of the actual by using the optimal turning conditions. Good agreement between the actual and the predicted results has been observed (the improvement in the overall Grey relational grade was found to be as 0.20).

In the Taguchi method, the only performance feature is the overall Grey relational grade and the aim should be to search for a parameter setting that can achieve the highest overall Grey relational grade [9]. The Grey relational grade is a representative of all the individual performance characteristics. In the present study, the objective functions were selected in relation to the parameters of the material-removal rate, the cutting force and the surface roughness. The importance weights of the material-removal rate, the cutting force and the surface roughness were equally adjusted to be 0.33.

The results show that using the optimal parameter setting ($V_3 f_1 d_1$) causes a lower cutting force and surface roughness with a higher material removal rate and hence a better surface finish.

5 CONCLUSIONS

In this study, the Grey-based Taguchi method was applied for the multiple performance characteristics of turning operations. A grey relational analysis of the material-removal rate, the cutting force and the surface roughness obtained from the Taguchi method reduced from the multiple performance characteristics to a single performance characteristic which is called the grey relational grade. Therefore, the optimization of the complicated multiple performance characteristics of the processes can be greatly simplified using the Grey-based Taguchi method. It is also shown that the performance characteristics of the turning operations, such as the material removal rate, the cutting force and the surface roughness are greatly enhanced by using this method.

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