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Optimizing Turning Parameters Using Taguchi Method to Maximize Tool Life and Minimize Wear and Vibration

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Abstract

Turning is an essential machining process utilized across various industrial sectors, including aerospace, automotive, and engineering. Optimizing parameters such as cutting speed, feed rate, and depth of cut is crucial for extending tool life, reducing vibrations, and enhancing machining efficiency. This study examines the effects of these parameters on EN31 high-carbon chromium steel through the Taguchi method and ANOVA. EN31 is chosen for its superior mechanical properties, rendering it suitable for high-wear applications. A total of 27 experiments were performed using an orthogonal array (L27) to evaluate tool wear and vibrations, with S/N ratio calculations employed to identify optimal conditions. Findings indicate that feed rate is the predominant factor influencing tool wear (61.11%), while cutting speed significantly affects vibrations (76.30%). This analysis provides valuable insights for minimizing tool wear and improving machining accuracy in practical manufacturing contexts.

Major Findings: *Feed rate had the greatest influence on tool wear (61.11%), followed by cutting speed (25.07%) and cut depth (9.61%). Cutting speed had a substantial impact on vibration (76.30%), whereas cut depth and feed rate contributed 15.99% and 5.58%, respectively. The ideal machining settings reduced tool wear and vibration, as shown by S/N ratio and ANOVA studies.*

Keywords: *ANOVA, EN31, Taguchi Method, Tool Wear, Vibration*

1.0 Introduction

'Turning' operation is widely utilized in aerospace, machinery design, automotive, metal removal operation. As one of the most significant methods for advancement in industrial sector, the analysis of metal cutting is centred on on several key areas, including tool characteristics, work material properties, efficiency of output and system variables. The enhancement of overall production efficiency is contingent upon the optimisation of these process variables. By identifying critical variables like cut depth, speed of cutting and rate of feed industries can improve process outcomes while minimizing variations, ultimately leading to lower production costs.

In real-world machining scenarios, accurately predicting tool life and production time can be challenging due to the absence of universally applicable machining theories. As a result, manufacturers often rely on empirical equations, which involve various constants that are not easily accessible and depend on multiple factors. The complexity of collecting and managing this data in a workshop setting further complicates the task. This paper investigates and optimizes the cut depth, speed of cutting and rate of feed for EN31 steel in conventional

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turning machines. By doing so, it aims to improve tool life and machining efficiency, offering practical solutions to the challenges faced in real-world manufacturing environments[1-4].

The Taguchi technique is a powerful statistical tool used to optimize process parameters. It use orthogonal arrays to systematically assess the impact of various factors with a smaller number of tests. This approach uses Signal-to-Noise (S/N) ratios to measure performance characteristics, classifying them as "smaller the better," "larger the better," or "nominal the best," depending on the goals. The Taguchi technique increases production efficiency while reducing unpredictability by determining the best amounts of machining parameters.

Analysis of Variance (ANOVA) extends the Taguchi approach by analyzing the statistical importance of each element on the output. ANOVA calculates the percentage contribution of each parameter to the observed variability, allowing for a better understanding of the process. The Taguchi technique and ANOVA provide a complete framework for assessing and optimizing machining processes.

2.0 Literature Review

This intends in assessing the extent of study's findings endeavours and accomplishments of different investigators in dynamic behavioural assessments discipline. This initiative aimed to acquire current expertise, assess past accomplishments, and evaluate potential for further development in this domain. The subsequent findings of their research are outlined below.

Ramanuj Kumar *et al*[5]., scoped out the coated carbide's multilayer insert which exhibited superior performance than uncoated carbide insert at elevated speed rate of cutting. This method is reliably employed for AISI D2 steel hard machining. Highly effective models of analytical are developed. The analysis of costs demonstrated the efficacy of Al_2O_3 coated carbide inserts. The lifespan of the coating insert of carbide laminate is similar to that of tool life, exceeding that of a without coating insert during sequential machining with carbide inserts.

Sanjeev Saini *et al.*,[6] optimized surface irregularities and tool wear prediction utilizing RSM for hard turning, finding that enhancing speed of cutting and minimizing the rate of feed improved surface finish while increasing tool wear.

Samir Khamel *et al.*,[7] investigated the AISI 52100 bearing steel's hard turning utilising the tool called 'CBN', emphasising roughness of surface and cutting forces. The study demonstrated cutting speed and rate of the feed which have a considerable impact on the life of the tool, as evidenced by the outcomes of ANOVA.

Sıtkı Akıncıoğlu *et al.*[8] utilised the technique called 'Taguchi' for surface roughness optimization in turning process of super alloy Hastelloy C22 with tool that's been treated cryogenically. ANOVA identified critical factors, and the study confirmed that deep cryogenic treatments enhanced tool wear resistance.

Ahmet Hasçalık *et al.*[9] utilized Ti-6Al4V and subjected to testing regarding tool life while maintaining consistent parameters of the machining. The results of this investigation indicate that cut depth has a substantial effect on life of tool.

Miguel Mandú Bonfá *et al.*[10] pinpointed the minimal lubricant needed for cutting fluid turning of AISI D6 hardened steel. Using polycrystalline cubic boron nitride tools bound with Al_2O_3 ceramic and TiN coatings, each path ensures precision and efficiency in material processing. Dry cutting differentiation were additionally examined. Through the use of a scanning electron microscope, analyses of tool wear are conducted. "Using MQL, the tool's flanking face and workpiece achieved better results than dry cutting.

Hamdi Aouici et al.,[11] studied flank wear using CBN cutters for turning AISI H11 hardened steel. Findings showed that rate of feed, cutting duration, and speed of cutting, and combined affect flank wear, with cutting speed and time having the most impact. ANOVA and RSM are utilized for analysis. The significant variables influencing flank wear were the cutting speed and cut time.

T. Tamizharasan *et al.*[12] elucidated the various characteristics that are related to tool wear, component quality, and tool life, and also how they affect the life of the tool and factors which removes material, as well as the process economics. The most basic solution is the utilisation of a lathe for the hard turning procedure. The high-performance CBN inserts are used alongside a

robust tool holder engineered to support precision cutting operations. The hard turning was performed on the crank pin material of the engine

Jing Sheng *et al.*[13] In this inquiry, the coupling was examined in relation to the lowest cutting tool wear, and a method known as simulation was employed to determine the turning features. The assessment degree was assumed to be the area of the surface to be machined. Consequently, the cutting temperature that yielded the least benefit in terms of cutting tool degradation was identified. The cutting factors coupling was established with the most minimal wear from the cutter, as evidenced by the enhancement in temperature and factors for Cutting between orthogonal tests.

Mustafa Kuntoglu *et al.*[14] entails the use of the Taguchi technique to conduct experiments and optimisation processes with three factors as independent variables during the turning of AISI 1050. In the course of metal processing, the acoustic emission and tangential cutting force were implemented to ascertain the cutting tool's condition. The tool point is the most effective, and the speed of the cutting is approximately 45% more efficient, according to the ANOVA. Roughly 35% of overall is attributed to tool wear.

D.K. Ojha *et al.*,[15] determined the tool's life by identifying the most suitable path upon the particulars that is within the steady wear area and extrapolating the tool's time to failure. The tool's shortest, longest, and anticipated lifespan prediction is done by neural network. The distinction within multiple regressions and neural networks is the most likely indicator of the former's superiority. Additionally, the study recommends an approach for continuous monitoring of the store floor's method use and the updating and/or achieving of the tool life estimate, while considering suggestions from floor shop.

Muhammad Younas *et al.*,[16] found factors for the turning of alloy Ti6Al4V. Experiments were conducted to optimise a total of four important factors for eliminating material, surface irregularities, and cutting energy wear rate in a dry conditions using H13 carbide inserts (uncoated). To construct a model, the AHP been implemented in conjunction with empirical analysis and Grey Relational Analysis (GRA).

Denis Boing *et al.*,[17] intended to showcase and engage in a discussion regarding the instrument's performance evaluation. Making use of WRM Method and model for tool life prediction pulled from instrument and PCBN software was incorporated for rough turning capabilities. In the initial stages of the tool's lifespan, the WRM wear element is determined through the concentrate variances microscopy. Additionally, the least squares approach is used to determine the unit's wear rate, and guided life of tool is based on how much material is taken from tool, which is referred to as the "end-of-tool" survival condition. The tool-life paradigm that was developed effectively forecasted the number of defects that would occur in the tool. The approach and model that were developed demonstrate a significant reduction in time during exploratory machining tests. This was achieved by optimising the machining procedure and expediting the evaluation and production of cutting tool grades. The process of machining is optimized, the cutting tool grades are provided, and the study is facilitated by the technique and the devised model, which causes a significant reduction in machining time.

P. Sivaiah *et al.*,[18] current study is grounded on the enhancement of the cutting capabilities of the specified AISI 304 by employing a Minimal level of Quantity Lubrication (MQL) tool with an acceptable machinability surface quality. An equivalent evaluation of turning efficacy was conducted in this study employing an individual texturing tool that was prepared with specimen pit holes and an innovative hybrid tool that was produced with round dimples and straight grooves, respectively, during specified material machining operation. The cutting velocity was also monitored. It was discovered that the roughness of the surface reached its highest point, the suggested tool hybrid texture greatly reduced temperature of cutting and wear of tool flank.

These studies together illustrate the importance of cutting parameters such as surface defects, cut depth, cutting speed, feed rate, tool life, tool wear, and machining efficiency over a wide range of materials and tooling techniques. Many people use optimization methods such as the Taguchi method, ANOVA, and neural networks to enhance machining results. In this study, a mixture of these methods is used to investigate the turning of EN31 high-carbon chromium steel, which is noted for its hardness, wear resistance, and strength. The purpose of this research is to determine the optimal machining settings for decreasing tool wear and vibrations, as well

as to give practical solutions for enhancing production efficiency.

3.0 Materials and Methods

Calculations must be made for cut depth, feed rate, and speed of cutting during the cutting process. The presented study employs series-based Taguchi system variable design and variable optimization to enhance tool life and vibration. The selected material for examination is EN31 (50mmdia and 200mmlength) high-carbon chromium steel widely used in engineering applications for components that need to be extremely wear-resistance, hardness (64 HRC) and high strength. EN31 is known for its excellent mechanical properties, including high fatigue strength and toughness. Typically, it's been employed in the production of bearings, tools, dies, and other parts subjected to heavy wear and stress[19]. The EN31 sample's chemical composition was utilised in this research was verified through spectro analysis, as shown in Table 1. Figure 1 shows the Photograph of EN31 samples.



Figure 1. Photograph of EN31 samples.

3.1 Experimental Design

The optimal factors determined utilizing the method 'Taguchi' in order to achieve decreased vibration during the turning phase and a longer life of tool with minimal tool wear. Using orthogonal arrays to gather distinctive data, Taguchi's approach analyses the outputs to determine the perfect variables for the procedure. Three kind of output characteristics are attainable when examining the S/N ratio in accordance with Taguchi design: the nominal, lower and higher the better. With a limited number of trials, this method analyses the entire variable range using the architecture of orthogonal arrays. Higher ratio of S to N are correlated with better output quality. The ideal set of procedural settings is therefore the one that yields the highest performance S/N ratio. Classifying the statistically significant process variables is a common use of ANOVA. Lower and higher is preferable for production time and tool life respectively when it comes to optimal machining efficiency features[20,21].

The lower the better criteria equation below was used to calculate the S/N ratio values that corresponded to tool wear experimental values.

$$S/N=10\log_{10}\frac{1}{n}\sum_{i=1}^{n}y2$$

(for criterion of lower better)

The following equation for the lower the better condition was used to calculate S/N ratio values that corresponded to the vibrations values.

Table 1. Work piece chemical composition (%)

C	Mn	Si	Cr	Ni	P	S
1.20%	1.60	0.3	1.55	0.005	0.05	0.04



Figure 2. Photograph of lathe operation showing the experimental trials.

$$S/N=10 \log_{10}\frac{1}{n}\sum_{i=1}^{n} y2$$

(for criterion of lower better)

3.2 Parameters and Experimental Design (DOE)

A more methodical approach to conducting tests is aided by 'DOE'. Table 2 lists the process variables along with their respective levels. For the analysis of the complete variable range, an orthogonal array of Taguchi's is utilized alongside limited number of tests. The evaluation implemented a well-organised Taguchi method utilising orthogonal arrays of L27 to investigate the influence of three essential variables like cut depth, speed of cutting and feed rate each of which was evaluated at three separate stages. Figure 2 shows the photograph of lathe operation showing the experimental trials.

4.0 Result and Discussions

The experimentation of total 27 trials has been conducted. The experimental results for vibration and tool wear, as well as the corresponding S/N ratio, are presented in Tables 3 and 5. The vibration and tool wears small values are typically desired to ensure high-quality and precise machining. Therefore, the independent variables are established using the orthogonal matrix, and tool wear main effect shows in the Figure 3 and calculation of S/N ratio is done as illustrated Table 4 since the smaller the data, the better it is for vibration and tool wear. In the same vein, vibration is being assessed, and the main impact graphs are generated. Calculation of vibration S/N ratio is done as illustrated in Table 6 and main effect of vibration shows in the Figure 4, and independent variables are arranged in accordance with the orthogonal matrix.

Table 2. Processing levels and variables

Levels	Cutting Speed(m/min)	Feed (mm/rev)	DOC (mm)
1	100	0.08	0.20
2	150	0.16	0.40
3	200	0.24	0.60

Table 3. Tool wear and S/N ratio experimental results

Exp No.	Cutting Parameter Level				
	A	B	C	Tool wear(mm)	S/N Ratio
	Cutting Speed	Feed Rate	Depth of Cut		
1	100	0.08	0.2	0.069	23.22302
2	100	0.08	0.4	0.103	19.74326
3	100	0.08	0.6	0.124	18.13157
4	100	0.16	0.2	0.079	22.04746
5	100	0.16	0.4	0.112	19.01564
6	100	0.16	0.6	0.131	17.65457
7	100	0.24	0.2	0.086	21.31003
8	100	0.24	0.4	0.122	18.2728
9	100	0.24	0.6	0.14	17.07744
10	150	0.08	0.2	0.048	26.37518
11	150	0.08	0.4	0.078	22.15811
12	150	0.08	0.6	0.098	20.17548
13	150	0.16	0.2	0.057	24.8825
14	150	0.16	0.4	0.089	21.0122
15	150	0.16	0.6	0.109	19.25147
16	150	0.24	0.2	0.068	23.34982
17	150	0.24	0.4	0.101	19.91357
18	150	0.24	0.6	0.132	17.58852
19	200	0.08	0.2	0.04	27.9588
20	200	0.08	0.4	0.07	23.09804
21	200	0.08	0.6	0.081	21.8303
22	200	0.16	0.2	0.054	25.35212
23	200	0.16	0.4	0.086	21.31003
24	200	0.16	0.6	0.104	19.65933
25	200	0.24	0.2	0.065	23.74173
26	200	0.24	0.4	0.081	21.8303
27	200	0.24	0.6	0.096	20.35458

Table 4. Tool wear S/N ratios response table

Level	A	B	C
1	19.61	22.52	24.25
2	21.63	21.13	20.71
3	22.79	20.38	19.08
Delta	3.18	2.14	5.17
Rank	2	3	1



Figure 3. Tool wear main effect plots.

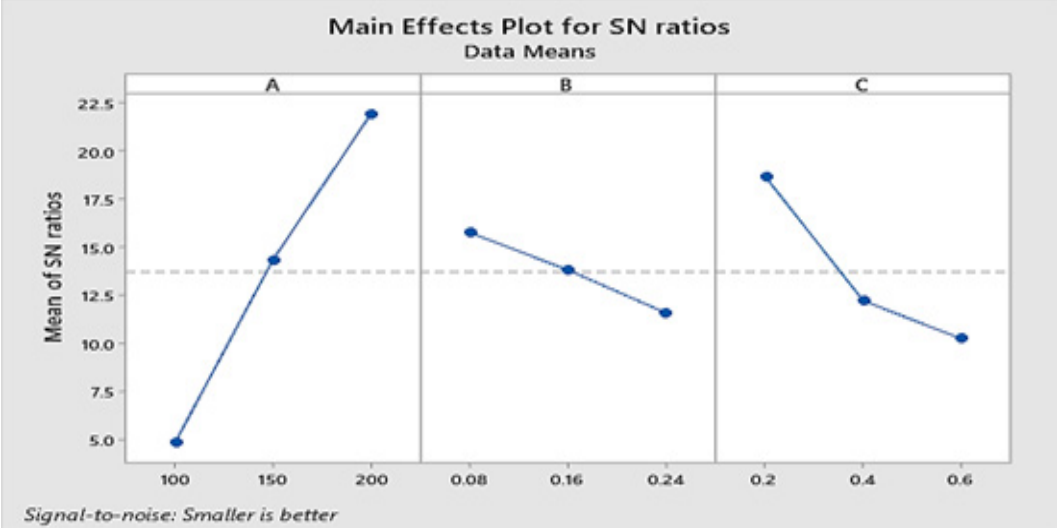


Figure 4. Vibration main effect plot.

Table 5. Vibration and S/N ratio experimental results

Exp No.	Cutting Parameter Level				
	A	B	C	Vibration(m/s²)	S/N Ratio
	Cutting Speed	Feed Rate	Depth of Cut		
1	100	0.08	0.2	0.245	12.21668
2	100	0.08	0.4	0.533	5.465456
3	100	0.08	0.6	0.647	3.781914
4	100	0.16	0.2	0.383	8.336025
5	100	0.16	0.4	0.643	3.835781
6	100	0.16	0.6	0.786	2.091549
7	100	0.24	0.2	0.552	5.161218
8	100	0.24	0.4	0.785	2.102607
9	100	0.24	0.6	0.952	0.427261
10	150	0.08	0.2	0.065	23.74173
11	150	0.08	0.4	0.198	14.0667
12	150	0.08	0.6	0.257	11.80134
13	150	0.16	0.2	0.072	22.85335
14	150	0.16	0.4	0.253	11.93759
15	150	0.16	0.6	0.319	9.924186
16	150	0.24	0.2	0.151	16.42046
17	150	0.24	0.4	0.306	10.28557
18	150	0.24	0.6	0.394	8.090076
19	200	0.08	0.2	0.032	29.897
20	200	0.08	0.4	0.083	21.61844
21	200	0.08	0.6	0.11	19.17215
22	200	0.16	0.2	0.05	26.0206
23	200	0.16	0.4	0.097	20.26457
24	200	0.16	0.6	0.113	18.93843
25	200	0.24	0.2	0.068	23.34982
26	200	0.24	0.4	0.097	20.26457
27	200	0.24	0.6	0.128	17.8558

Table 6. Vibration's S/N ratios response table

Level	A	B	C
1	4.824	15.751	18.666
2	14.347	13.800	12.205
3	21.931	11.551	10.231
Delta	17.107	4.200	8.435
Rank	1	3	2

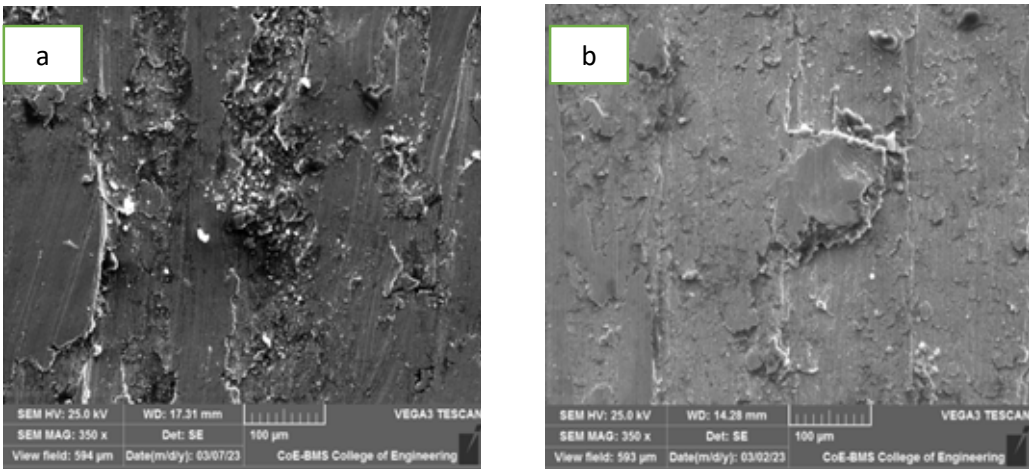


Figure 5. SEM images of machined surface indicated material side flow at **(a)** DOC of 0.40 mm FR of 0.0.08 mm/rev, and Vc of 100 m/min. **(b)** DOC of 0.80mm, FR of 0.16 mm/min, and Vc of 150 m/min.

The noticeable adherent mass in the image's centre is most likely the consequence of a Built-Up Edge (BUE) or Built-Up Layer (BUL) on the cutting instrument. BUE is formed when material from the workpiece clings to the cutting tool's edge owing to excessive friction and high temperatures at the cutting interface. This attached material might then move back to the workpiece surface, resulting in imperfections and a poor finish. The presence of BUE or BUL not only impairs the dimensional correctness of the machined item, but it also reduces the tool's cutting efficiency. The rough texture and greater regions of attached material may be attributable to excessive cutting pressures, which are often induced by a deeper cut or increased tool wear. According to the ANOVA study, depth of cut has a substantial effect on cutting forces, which directly affect surface quality. Over time, these pressures exacerbate tool wear, particularly if the tool is not properly maintained or replaced. A worn tool edge is less capable of making clean cuts, which increases material adhesion and degrades surface quality. This cycle of material adhesion and tool wear emphasizes the significance of adjusting machining settings. Reducing the depth of cut and maintaining ideal cutting rates helps reduce BUE production, extend tool life, and assure a better surface finish. Regular tool inspection and replacement are also crucial for machining accuracy. Tool wear can lead to more material adhesion and rougher surfaces, as the worn tool edge fails to produce a clean cut as noticed in the Figure 5.

Table 7. ANOVA for S/N ratio Tool wear

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution	Rank
A	2	0.013325	0.006662	87.57	0.000	25.07	2
B	2	0.033819	0.016910	222.25	0.000	61.11	1
C	2	0.005519	0.002760	36.27	0.000	9.61	3
Error	20	0.001522	0.000076				
Total	26	0.054185					

Table 8. ANOVA for S/N ratio of vibration

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution	Rank
A	2	1.07926	0.539628	239.13	0.000	76.30	1
B	2	0.06373	0.031866	14.12	0.000	5.58	3
C	2	0.22632	0.113161	50.15	0.000	15.99	2
Error	20	0.04513	0.002257				
Total	26	1.41444					

4.1. Variance Analysis

The independent variable percentage contribution on dependent variable is determined utilizing variance analysis. Table 7 clearly indicates that feed rate accounts for 61.11% of tool wear, whereas cutting speed and cut depth contribute approximately 25.07% and 9.61% respectively. The vibration is majorly being influenced by the speed of the cutting compared to cut depth and feed rate which can be seen in Table 8. The cutting speed accounts for 76.30% of the influence, whereas the depth of cut contributes 15.99%, and the feed rate follows with an impact of 5.58%.

5.0 Conclusions

For the purpose of optimizing the turning operation, the 'Taguchi' factor design technique was applied in the research of vibration and tool wear. The experimental findings of the research make it possible to draw the conclusions which are shown.

- Among the parameters that determine tool wear, feed rate is the most significant, accounting for 61.11% of the variability in tool wear.
- When it comes to vibrations, cutting speed is the most important factor, as it accounts for 76.30% of the impact. This is an essential factor in maintaining accuracy in machining.
- Applying the Taguchi approach allowed for the achievement of optimal machining settings, which resulted in an increase in tool life and a decrease in surface defects.
- Within the realm of tool wear and vibration, the depth of cut is a relatively insignificant factor, accounting for 9.61% and 15.99% of the total, respectively.
- In industrial applications, statistical techniques such as Analysis of Variance (ANOVA) and Taguchi methods provide a systematic framework for assessing and optimizing machining settings, hence lowering the amount of trial and error that need be performed.

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7.0 Authorship Contribution

Nagesha N: Conceptualization, Data collection, analysis, Methodology, Visualization, original draft. **B. S. Praveen Kumar:** Resources, Writing - review and editing.

8.0 Author Designation

N. Nagesha- Research scholar; B. S. Praveen Kumar- Associate professor

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