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학술논문

Efficiency Estimation of Process Plan Using Tolerance Chart

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ABSTRACT

This paper presents a new method for assessing the efficiency of production process plans using tolerance chart to lower production cost. The tolerance chart is used to predict the accuracy of a part that is to be produced following the process plan, and to carry out the quantitative measurement on the efficiency of the process plan. By comparing the values of design tolerances and their corresponding resultant tolerances calculated using the tolerance chart, the process plan that is incapable of satisfying the design requirements and the faulty production operations can be identified. Similarly, the process plan that imposes unnecessarily high accuracy and wasteful production operations can also be identified. For the latter, a quantitative measure on the efficiency of the process plan is introduced. The higher the unnecessary cost of the production, the poor is the efficiency of the process plan. A coefficient is introduced for measuring the process plan efficiency. The coefficient also incorporates two weighting factors to reflect the difficulty of manufacturing operations and number of dimensional tolerances involved. To facilitate the identification of the machining operations and the machined surfaces, which are related to the unnecessarily tight resultant tolerances caused by the process plan, a rooted tree representation of the tolerance chart is introduced, and its use is demonstrated. An example is presented to illustrate the new method. This research introduces a new quantitative process plan evaluation method that may lead to the optimization of process plans.

Key words : Tolerance chart, Process plan, Rooted tree, Efficiency estimation

1. Introduction

In today's highly competitive global industrial environment, most manufacturing companies have to fabricate a larger variety of products at lower cost and shorter lead-time, in order to survive and to compete effectively. To improve the efficiency of the production processes that turn mechanical designs into products, the production process plans that are used to guide these production processes need to be optimized for high efficiency. Most research efforts on Computer Aided Process Planning (CAPP) to date have been focused on the automated generation of the process plans[1-5]. A few researchers have contributed to the quantitative evaluation of the efficiency or performance of the process plan itself[6].

The tolerance chart, originally used as a tool to plan and verify a manufacturing sequence using the dimension and tolerance information of a design, is also a precise technique for planning the manufacturing process of a given design that requires successive machining operations[7]. Over the past years, extensive researches have been carried out on the automated generation of tolerance chart. A graph-theoretic method for making a tolerance chart was proposed in [8]. A method for constructing tolerance chart using a matrix-tree-chain scheme and a tracing approach was introduced in [9]. A procedure for recognizing dimension chains in a tolerance chart using a list expression was presented in [10]. A tree-theoretic expression for producing tolerance chart was first proposed in [11] and an algebraic approach for identifying dimensional chains using a tolerance chart later introduced by Ji in [12].

In this work, a method for quantitatively estimating and measuring the efficiency and performance of a process plan for machined parts is introduced. The tolerance chart is used to predict the accuracy of the part that is to be produced following the process plan, and to carry out the quantitative measurement on the efficiency of the process plan. The tolerance chart provides the resultant information of a process plan, such as the sequence of manufacturing operations

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involved, and the resultant dimensional tolerances of the surfaces that are machined according to the process plan.

In manufacturing, or specifically during the machining of mechanical part, no mechanical features can be produced in their exact dimensions and shape. For the required size accuracy, design dimensional tolerances (so simply design tolerances), t_{Di}, are specified on the engineering drawing to specify the allowed size variations. These design specifications should be met to satisfy the design requirements. The final dimensions of the part are produced by a sequence of machining operations, following the process plan. The accuracy of each of these final dimensions is determined by several machining operations applied to the related surfaces and the cutting parameters used, as specified in the process plan, and illustrated by the tolerance chart. The tolerance chart also presents the resultant tolerance of the final dimension, as a result of several machining steps. This resultant dimensional tolerance (or resultant tolerance), t_{Ri}, cannot specify the exact value of the final dimension, but it presents the possible range of variation of the final dimension. Specifically, there exist three possibilities:

1) $t_{Ri} > t_{Di}$ - The resultant tolerance is looser than the design tolerance. The process plan is not acceptable and not efficient since the design requirement is not satisfied. Related machining operations have to be identified and rearranged, and new machining parameters have to be assigned.
2) $t_{Ri} = t_{Di}$ - The resultant tolerance is equal to the design tolerance. The process plan is optimal since the design requirement is just satisfied with the machining operations specified in the process plan.
3) $t_{Ri} < t_{Di}$ - The resultant tolerance is tighter than the design tolerance. The machined feature is unnecessarily accurate. The process plan caused unnecessarily high production cost. For this reason, the efficiency of the process plan is considered "poor". The larger the difference between the two tolerances, the higher the production cost, the worse the efficiency of the process plan is.

Each machined part has many final design dimensions and tolerances. For every resultant tolerance in case 1), the corresponding parts of the process plan have to be modified. It is unlikely that the resultant tolerance will fall in case 2). For most situations, the process plan will lead to the result of case 3).

In this work, a method for the quantitative measurement on the efficiency of the process plan is introduced for case 3). By comparing the values of design tolerances and their corresponding resultant tolerances calculated using the tolerance chart, the process plan that imposes unnecessarily high accuracy and wasteful production operations is identified. Similarly, the process plan that is incapable of satisfying the design requirements and the faulty production operations can also be identified for modification. A rooted tree technique is used to recognize both production operations and the dimensional tolerances that are related to the resultant dimensional tolerance.

2. Tolerance Chart and Rooted Tree

2.1 Tolerance Chart

A tolerance chart is a graphical expression for the machining sequence of a mechanical part's process plan [3]. The chart is used to find whether a specific machining sequence is appropriate for producing the part with a given resultant dimension and tolerance, and whether material removal operations are properly assigned during the machining of the part. For an example design of steel plug given in Fig. 1, its tolerance chart is illustrated in Fig. 2 [13]. In this figure, machining operations and their sequence, as the results of a process plan, are shown on the top left. Design specifications such as dimensions and tolerances are shown at the lower left side. Each machining operation is represented by a machining symbol line arrow and its machining parameter. The machining symbol consists of an arrow that points to the machined surface, and a small black circle that indicates the datum for the machining operation. The head of the arrow points to the machined surface.

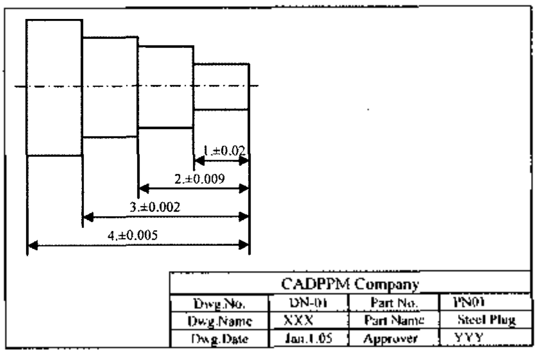
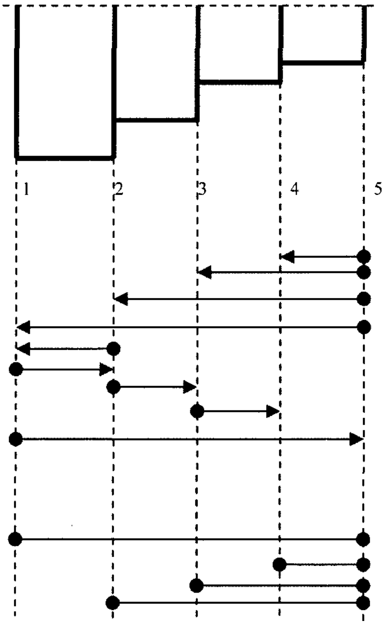


Fig. 1. An example design of a steel plug.

The tolerance chart is used to calculate the tolerance stacks on the resultant dimensions on the bottom right. These calculated results are compared with the

Seq. No.	Operation	
	No.	Name
1	10	Turning
2	10	Turning
3	10	Turning
4	10	Turning
5	20	Turning
6	30	Grinding
7	40	Grinding
8	50	Grinding
9	60	Grinding



Working Dim.		Stock Removal		
Mean	±Tol.	Mean	±Tol.	Chain
0.979	.003	Solid		
1.994	.003	Solid		
3.003	.003	Solid		
4.031	.010	Solid		
1.008	.004	.020	.017	-5,4,-3
1.000	.001	.008	.005	-6,5
1.000	.003	.017	.014	-7,-6,5,3,-2
1.000	.015	.032	.029	-8,-7,-6,5,3,-1
4.000	.001	.011	.008	-9.5.3

B/P Dimension	
Mean	±Tol.
4.000	.005
1.000	.020
2.000	.009
3.000	.002

Resultant Dimension		
Mean	±Tol.	Chain
4.000	.001	9
1.000	.020	9,-8,-7,-6
2.000	.005	9,-7,-6
3.000	.002	9,-6

Fig. 2. Tolerance chart for the machined steel plug.

given design tolerances to ensure that the part is manufactured within the required design specifications. The chart is also used to calculate the tolerance stacks for stock removal and compare with the stock removal allowances. These values are both listed in the table on the top right. A step-by-step comparison of the stock removal tolerance and allowance values ensures sufficient excessive material is left for the following machining operations. The working dimension of the machined surface in the machining sequence is shown at the top right, matching the dimensions illustrated on their left. In this table, the amount of stock removal is calculated and compared with the cutting volume of the workpiece.

To measure the efficiency of a process plan quantitatively, each machining operation that produces one or more feature surfaces should be recognized and evaluated individually. However, each vertical line in a tolerance chart represents one or more machined surfaces. The machined surfaces are thus not clearly expressed individually. An alternative representation becomes necessary.

2.2 Rooted Tree

A rooted tree is a tree that has a vertex (or node) called the root. A vertex of one degree except the root is called as a leaf. A branch is a path from a vertex to a leaf. In this work, a machining sequence within a tolerance chart is represented using a rooted tree. This representation contains information about machining operations, their machined surfaces and the sequence of these operations. Furthermore, a machining operation is associated with a locating surface and a machined surface. The first locating surface in the tolerance chart is the root of the tree. A node represents a machined surface or a locating surface, and a branch represents a machining operation with a related dimension between the two surfaces. The rooted tree representation for the tolerance chart shown in Fig. 2 is given in Fig. 3.

In this representation, each machined surface is uniquely expressed with a label of four digits at the nodes. The first two digits are used to indicate the serial

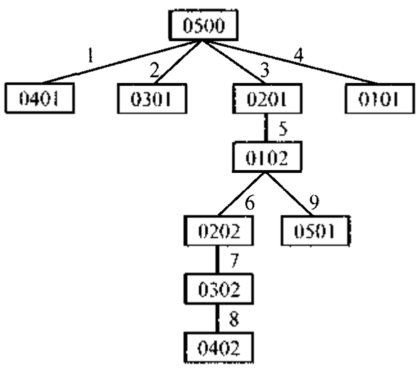


Fig. 3. A rooted tree of the tolerance chart.

number of the surface on the drawing, numbered from left to right. The last two digits are used to specify the serial number of the cut surface in machining. The first left vertical line in Fig. 2 represents the surface that is machined by two operations and the surfaces produced by these two operations are expressed by 0101 and 0102 in Fig. 3. In 0101, the first two digits, 01, is surface number and the last two digits, 01, indicate the first cut made from this surface. In the second label, 0102, the first two digits, 01 indicate the same surface and the last two digits, 02, record the second cut.

A path connecting one node to the other node in the tree represents a machining operation, and the machined dimension and tolerance between two surfaces. These dimension and tolerance are the results of all the machining operations that are involved on the path connecting the two nodes. Therefore all edges on the path should be identified to find the machining dimension and tolerance between the two surfaces. All related machining operations can be identified by searching from all the branches of a reversed path, which starts from a surface of the two and ends to the other surface through the root. For example, a dimensional tolerance between surface number 1 and surface number 5 that is machined by the last operation in Fig. 2 is a dimensional tolerance between the machined surface 0102 and 0501 in the rooted tree of Fig. 3, and the related edges are the pre-machined surfaces 0500 and 0201. So the stock removal and the tolerance between 0102 and 0501 are 0.011 and 0.008 (mm), respectively.

2.3 Resultant Dimension and Related Sub-rooted Tree

One of the results in a tolerance chart is the resultant dimension. The calculated tolerances of resultant dimensions are compared with corresponding design tolerances to evaluate the efficiency of the process plan. If these two tolerances are different, the machining operations and the surfaces related to the resultant dimensions in the process plan need to be identified or modified, since a larger resultant tolerance represents a production process that failed to satisfy the design requirement, while a smaller resultant tolerance represents unnecessarily high machining accuracy and cost. In the former case, it's not efficient to apply the process plan. In the latter case, the efficiency of the process plan is evaluated. Identification and comparison of the two tolerances are carried using the tolerance chart. Since the rooted tree representation of the tolerance chart represents machining operations, their sequence, individually machined surfaces, and resultant dimensional tolerance, the related machining operations and surfaces can be identified by a search on the rooted tree.

One or more surfaces and their dimensional tolerances can be produced during one operation, and the information can be expressed by a set of line number on a tolerance chart. For example, four surfaces are machined by the operation number 10 and four dimensional tolerances of machined surfaces are created, and they are recorded as {1, 2, 3, 4} by their sequence numbers.

For different resultant and design dimensional tolerances, operations and dimensional tolerances that are used to machine the surfaces in the process plan are identified through the path in the rooted tree using the following procedure. Two surfaces that are associated with the resultant dimension/tolerance are first selected, and the reversed path that connects the two surfaces through the root is then identified on the rooted tree and the path is called as a sub-rooted tree. The related machining operations, machined surfaces, and their dimensions and tolerances, associated to this path, are also found. For the example shown in Fig. 2, the third resultant dimension and tolerance are 2.000 and 0.005, respectively. And the numbers of the related machining surfaces are 0302 and 0501 in Fig. 3. The related sub-rooted tree is shown by a reversed path in Fig. 4 and the set of related line numbers are {3,5,6,7,9}, and the five machining operations are involved.

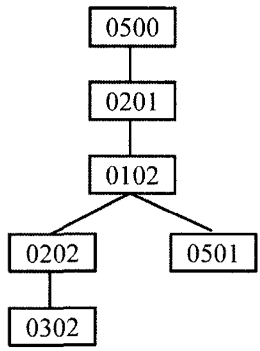


Fig. 4. A related sub-rooted tree.

3. Efficiency Estimation of a Process Plan

A process plan plays a major role in deciding the efficiency of the machined part and its production cost. The most efficient process plan of a part ensures its efficiency and requires minimum production cost.

However, to measure the quality or efficiency of a process plan involves many tasks, such as part feature recognition, process selection, machine tool selection and operation planning. One type of clear results of a process plan is the collection of resultant dimensions and tolerances of a machined part. In this work, the efficiency of a process plan is measured by comparing the differences between the resultant dimensional tolerance and the corresponding design tolerance.

3.1 Coefficient of a Process Plan Efficiency

A quantitative measure is introduced in this section to access the efficiency of the process plan. When a part is machined, various operations can be applied to produce the designed geometry, and the degree of difficulty of their operations differ each other. An operation can be applied to produce one or several surfaces. The coefficient for a process plan efficiency is reflected by the difference between the resultant dimensional tolerance and its corresponding design tolerance, presented in a tolerance chart.

In this work, two weighting factors for various machining operations and for different numbers of machined surfaces in an operation are introduced. The weighting factor for an operation can be determined by its degree of difficulty and importance. If the degree of both difficulty and importance of the operation is identical, the factor is divided by the number of operations involved. Otherwise, the values are assigned by the user. The other weighting factor is incorporated to consider the number of machined surfaces in an operation. The value of the weighting factor increases when the number of machined surfaces in an operation increases.

The efficiency measurement coefficient, E, of a process plan is defined using the two weighting factors as

$$E = \left(1 - \sum_{i=1}^{m}\sum_{j=1}^{n}\delta_i w_{ij}\right) \times 100(\%) \quad (1)$$

where, δ_i, has a value of either 0 or 1, depending upon whether the two dimensional tolerances are the same or not; m is the number of operations applied; n is the number of dimensional tolerances in the i^{th} operation; w_{ij} is a weighting factor of the j^{th} dimensional tolerance in the i^{th} operation ($w_{ij} = W_i * (1/n(dt_i))$); W_i is a weighting factor of the i^{th} operation. Values of W_is can be same or different according to the degree of machining difficulties including tolerances; and $n(dt_i)$ is the number of dimensional tolerances manufactured during the i^{th} operation.

3.2 A Procedure for Efficiency Estimation of a Process Plan

In this section, a procedure for the efficiency estimation of a process plan using the information of a tolerance chart represented in the rooted tree and the defined coefficient is presented. This procedure consists of the following steps:

1) Collecting the information, including machining operations and their sequence, needed by the tolerance chart, and the process plan of a part
2) Constructing the rooted tree to represent the tolerance chart
3) Deciding the number of operations and the set of surfaces machined in an operation using the operation or line number in the tolerance chart
4) Comparing the resultant dimensional tolerance and the corresponding design tolerance. If these two are identical assigning E = 100%. Otherwise, information related to the different dimensional tolerances is collected.
5) Changing the process plan if the calculated resultant dimensional tolerance is larger than the corresponding design tolerance
6) Or, forming a sub-rooted tree related to the resultant dimensional tolerances using a reversed path in a rooted tree, and calculating the number of operations and selecting the set of line number in the sub-rooted tree
7) Calculating the process plan efficiency by the coefficient E.

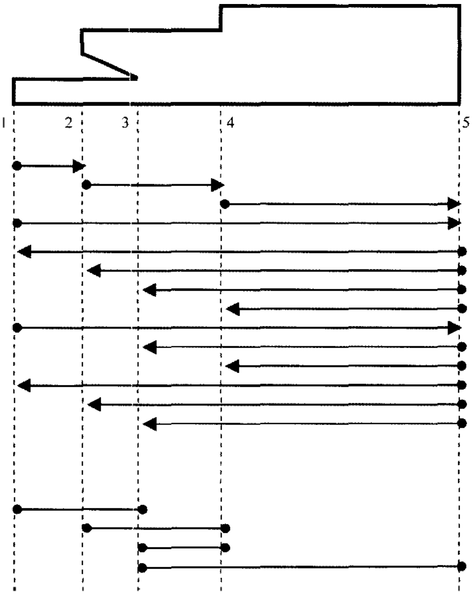
4. A Case Study

The presented procedure for the efficiency measurement of a process plan is illustrated using an example shown in Fig. 5 [6]. In this figure, operation number, working dimension and tolerance, and stock removal and its tolerance for a part are given and calculated according to a process plan. A tolerance chart is drawn in Fig. 5 and its rooted tree representation is shown in Fig. 6.

In the tolerance chart, there exist 7 unique machining operations. These are: operation 010 in line {4}, operation 020 in lines {5,6,7,8}, operation 030 in line {9}, operation 040 in line {10}, operation 050 in line {11}, operation 060 in lines {12,13} and operation 070 in line {14}.

Three pairs of dimensional tolerances are different if one compares the tolerance values in the tables on the bottom left and the right of Fig. 5, and the resultant dimensional tolerances are more precise than design tolerances. The first different dimensional

Line No.	Op. No.	Working Dimension		Stock Removal	
		Mean	Tol.	Mean	±Tol.
1		8.2500	.2500	Solid	.2500
2		18.8500	.2500	Solid	.2500
3		28.1000	.2500	Solid	.2500
4	010	53.9000	.2500	1.200	1.000
5	020	53.4000	.1300	.5000	.3800
6	020	44.9000	.1300	.7500	.6300
7	020	38.8000	.1300	.1300	.1300
8	020	25.9000	.1000	1.000	.8500
9	030	53.2000	.2500	.2000	.1550
10	040	38.2000	.0500	.4000	.3350
11	050	25.3000	.0500	.4000	.3050
12	060	53.0000	.0500	.2000	.0750
13	060	44.3000	.2500	.4000	.3100
14	070	38.0000	.2500	.2000	.0750



Design Dimension		Resultant Dimension	
Mean	Tol.	Mean	±Tol.
15.0000	.1200	15.0000	.0750
19.0000	.0800	19.0000	.0750
12.7000	.0750	12.7000	.0750
38.0000	.1000	38.0000	.0250

Fig. 5. A traditional tolerance chart.

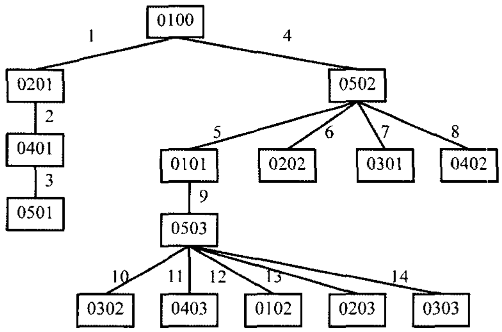


Fig. 6. Rooted tree for a tolerance chart.

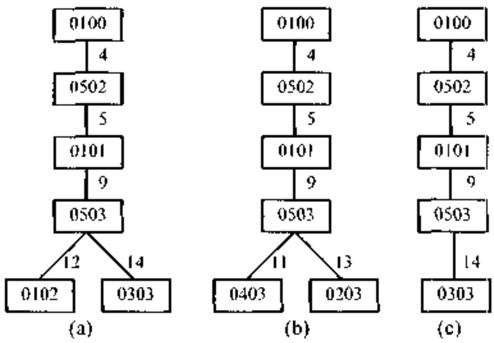


Fig. 7. Each sub-rooted tree for different dimensional tolerances.

tolerance is related to the values between the two machined surfaces, numbered 0102 and 0303 in a rooted tree of Fig. 6. The sub-rooted tree of the first different dimensional tolerance is shown in Fig. 7(a) and the set of related line numbers is {4, 5, 9, 12, 14}. When the surfaces associated with these line numbers are machined, five operations are involved since no more than one surface is machined in each operation. The second different dimensional tolerance is related to the nodes 0203 and 0403 in Fig. 6. The sub-rooted tree of it is shown in Fig. 7(b) and the set of related line numbers is {4, 5, 9, 11, 13}.

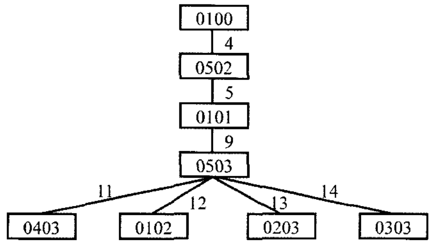


Fig. 8. Combined sub-rooted trees for different dimensional tolerances.

Five operations are involved. The same method is applied to the last different dimensional tolerance and Fig. 7(c) shows the corresponding sub-rooted tree. The number of production operations is four and the set of related line number is {4, 5, 9, 14}. The sub-rooted trees for the three pairs of different dimensional tolerances are combined and shown in Fig. 8, and the set of related line numbers is {4, 5, 9, 11, 12, 13, 14}. In this set, the line numbers with the same production operation is {12, 13} and the total number of production operations used is six although the total number of elements in the line number set is seven.

The measurement on the efficiency of the process plan of the example is carried out using Eq. (1). The weighting factor of each operation is identical, W_i = 1/7, W_{2j} = 1/28, W_{6j} = 1/14. The calculated efficiency coefficient, E = 25%. This indicates that the process plan for machining the part is far from ideal. Unnecessarily higher production cost is introduced by making the final dimensions of the part more accurate than the values specified by the design tolerances on the drawing. Using this procedure, one can quantitatively measure the efficiency of a process plan.

5. Conclusions

In the work, a new method for measuring the efficiency of a process plan for machining mechanical parts is introduced.

The tolerance chart is used to predict the accuracy of the part that is to be produced following the process plan, and to carry out the quantitative measurement on the efficiency of the process plan. By comparing the values of design tolerances and their corresponding resultant tolerances calculated using the tolerance chart, the process plan that is incapable of satisfying the design requirements and the faulty production operations can be identified. Similarly, the process plan that imposes unnecessarily high accuracy and wasteful production operations can also be identified. For the latter, a quantitative measure on the efficiency of the process plan is introduced. The higher the unnecessary cost of the production, the lower is the efficiency of the process plan. A coefficient for measuring the process plan efficiency is introduced. This coefficient also incorporates two weighting factors to reflect the difficulty of manufacturing operations and number of dimensional tolerances involved.

To facilitate the identification of the machining operations and the machined surfaces, which are related to the unnecessarily tight resultant tolerances caused by the process plan, a rooted tree representation of the tolerance chart is introduced, and its use is demonstrated. An example is presented to illustrate the new method.

This efficiency measure of a process plan reflects the extra manufacturing effort devoted in the machining of the part and the extra production cost beyond the minimum. Used in conjunction with other measures on the efficiency of the process plan, the proposed method allows process plan to be quantitatively evaluated and modified for its best performance.

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