Cutting Time Optimization Using Technology for CNC Machines

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Abstract: The paper considers a problem of cutting tool route formation in a generalized formulation. The paper also proposes a mathematical model of total cutting time minimization based on standard, chained and common cutting technologies. Simple and combined equidistant types of transitions between equidistant (cutting and idle), as well as the entry points (insertions) and exits (ejections) of the cutting instrument, are used as technological limitations. Total cutting time equals to the sum of idle moves, total stroke time and the amount of time spent on material insertion and cutting initialization. The problem is solved in two main steps. First step (preliminary) includes determining areas of common cutting and equidistant contours generation, considering information about common cutting. Second step (optimization) includes creation of entry and exit points array, followed by optimization working stroke and idle moves ratio, as well as optimization of entry points count to minimize total cutting time. Algorithms for determining common cutting areas and generation common equidistant are shown. The proposed model has been tested via “ITAS NESTING” software complex. The Great Deluge Algorithm has been used for computing experiment conduction. The results of experiment obtained using waterjet instrument shows that common cutting technology usage leads to shortening of total cutting time due to reduction of idle moves and number of needed entry points.

1 INTRODUCTION

A necessary stage in the automation of the preparation of control programs for CNC cutting machines is the solution of the task of forming a cutting tool path (TP) in accordance with a nesting layout containing details and information on their location on a sheet [1][2].

Usually, in works devoted to the optimization of the TP route, the idling length [3], [4] or the cost of cutting, [5][6] are used as the criterion. Standard cutting (all contours are processed by a continuous line, transitions are carried out at idle speed) or chain cutting (there are transitions on the run) are provided as a cutting technology, but when cutting with a waterjet machine, it is advantageous to use the common cutting technology, especially for long product pieces. This makes it possible to reduce the total cutting time due to the decrease of the length of the working stroke and the number of necessary tool insertion points. To use this technology in the formation of the TP, it is necessary to take into account new limitations on the model and algorithms.

The aim of the work is to develop and test an experimental model for minimizing the total cutting time, taking into account cutting technologies.

2 TASK DESCRIPTION

The input information for the formation of the TP is the nesting layout and technological parameters of the cutting (cutting method, idling speed, working stroke speed, insertion time, cutting width, etc.).

Let’s consider that the input nesting map contains m parts located at some distance from each other. The distance between the parts is greater than or equal to the predetermined gap size.

Some pairs of parts can be at the distance of cutting width d, with $d < gap$, which means that a common cut will be performed on this section. Parts could be nested inside each others to increase the cutting ratio.

Each part consists of one external and an arbitrary number of internal contours. We introduce a number of notation:

$outer_k$ – outer contour of the k-th part, $k = \overline{1, m}$;

$inner_k$– set of internal contours of the k-th part, $k = \overline{1, m}$;

In the situation where the part has no internal contours, $inner_k = \emptyset$.

A contour is to be considered as a closed geometric object (GO), made up of a set of segments and arcs, since most cutting machines work only with geometric primitives mentioned above [6].

In general, the formation of a TP consists of performing a number of steps that can be performed in different order:

– creating equidistant lines along which the contours of the parts will be cut (half the cutting width);

– generating the order of contour processing;

– setting the direction of processing for each contour (CW - clockwise or CCW - counterclockwise);

– determination of coordinates of entry (insertion) and exit (ejection) points for TP;

– selection and placement of specialized cutting technologies, such as bridges, jumpers, loops at contour corners, etc.

While forming a TP the technological features of cutting, including technological limitations (TL) and the cutting technology (CT) used, must be taken into account.

2.1 The model for minimizing the total cutting time

It is assumed that on the input nesting layout the parts can be paired, which complicates the model of minimizing the total cutting time, since the combined contours will have a common entry and exit point, i. e. not every contour will have its own entry and exit points.

To solve this problem, it is proposed to match the entry / exit points not for contours, but for their equidistant. Moreover, for contours that have a common cut, a common equidistant will be generated.

Now let's consider an ordered set of contours $C = (c_1, c_2, \dots, c_n)$ and equidistants $E = (e_1, e_2, \dots, e_n)$.

The function $eq : C \to E$ associates the contour with its equidistant. In the case where there are no pairs of aligned parts on the nesting layout, $n = m$. Otherwise, $m < n$, since the contours of the combined parts have one common equidistant.

Each i-th equidistant corresponds to a set of potential entry points P_i and exit points Q_i. In the process of forming the RI route, for each equidistant, a single insertion point $P_i^k \in P^i$ and the corresponding exit point $Q_i^k \in Q^i$ are chosen. The distance between the k-th output point of the i-th circuit and the s-th entry point of the j-th contour in the plane is denoted by $L(q_i^k, p_j^s)$.

The point on the i-th equidistant to which the transition from the insert point occurs, is denoted by $\overline{p_i}^k$, and the point from which the transition from the contour equidistant to the exit point occurs by $\overline{q_i}^k$. The distance $L(p_i^k, \overline{p_i}^k)$ is equal to the length of the approach on the i-th equidistant, the distance $L(\overline{q_i}^k, q_i^k)$ is equal to the retraction length.

The complete structure v, which uniquely identifies the TP, includes the following information:

P_{start} – start point of the cutting tool route;

$cord_j$ – order of processing the j-th contour in TP, $j = \overline{1, n}$ (contour number);

$ord(1), ord(2), \dots, ord(m)$ – permutation defining the sequence of equidistant contours traversal, where *ord(i)* is the equidistant number visited i-th in TP;

$e_i = eq(c_j)$ – j-th contour equidistant, $i = \overline{1, m}, j = \overline{1, n}$;

dir_i – i-th equidistant cutting direction (CW or CCW), $i = \overline{1, m}$;

p_i^k – i-th equidistant entry point, $i = \overline{1, m}$;

$\overline{p_i}^k$, – i-th equidistant cutting start point, $i = \overline{1, m}$;

q_i^k– i-th equidistant exit point, $i = \overline{1, m}$;

$\overline{q_i}^k$– i-th equidistant cutting end point, $i = \overline{1, m}$;

P_{end} – end point of the cutting tool route;

$trans_{ord(i), ord(i+1)}$ – a parameter denoting the type of transition between the exit point of the i-th equidistant and the entry point of the (i + 1) -th equidistant in the order of contour processing (has two values: 0 - working, 1 - idle) $i = \overline{1, m}$.

Objective function of the task of minimizing the total cutting time:

$$T_{cutting}(v) = \frac{L_{st}(v)}{V_{st}} + \frac{L_{im}(v)}{V_{im}} + T_{ins} \times N_{inp}(v) \to min \quad (1)$$

where $T_{cutting}(v)$ – total cutting time; $L_{st}(v)$– total length of tool stroke; V_{st}– stroke speed, i.e. tool cutting speed; $L_{im}(v)$– total length of idle movements; V_{im} – tool idle movement speed; $N_{inp}(v)$– number of insertion points; T_{ins}– constant, time of one insertion.

Function $L_{im}(v)$ depends on TP as follows:
$L_{im}(v) = L(p_{start}, p^s_{ord(1)}) + \sum_{i=1}^{m-1}[L(p^k_{ord(i)}, p^s_{ord(i+1)}) \times trans_{ord(i),ord(i+1)}] + L(q^k_{ord(m)}, p_{end})$ (2)

i. e. total length of idle movements between the contours of parts is reduced if there are working transitions in the route.

Total length of working strokes $L_{st}(v)$

$L_{st}(v) = \sum_{i=1}^{m-1}[L(e_i) + L(p^k_i, \overline{p_i}^k) + L(\overline{q_i}^k, q^k_i)] + \sum_{i=1}^{m-1}[L(q^k_{ord(i)}, q^s_{ord(i+1)}) \times (1 - trans_{ord(i),ord(i+1)})]$ (3)

where $L(e_i)$ the sum of the lengths of geometric primitives equidistant e_i (in the case of a regular equidistant, the sum is equal to the perimeter; in the case of a combined equidistant, the sum of the perimeters of the equidistant contours minus the length of the common face, since it must be taken into account only once).

Thus, if working transitions (chain cutting) are used instead of idle transitions between the contours, then the value $L_{st}(v)$ is increased on the nesting layout.

Consider $N_{inp}(v)$:

$N_{inp}(v) = m - \sum_{i=1}^{m-1}(1 - trans_{ord(i),ord(i+1)})$ (4)

i.e. the number of insertion points decreases with increasing the number of working transitions.

2.2 TP restrictions

In order to form an acceptable TP , it is necessary to take into account a number of technological limitations.

1. Equidistant. The cutting process assumes that to preserve the geometry of the work piece, the cutting must be carried out at some distance from the contour, called the *equidistant.* For external contours of parts, the equidistant is displaced outward, and for internal contours it is displaced inward [6].

2. Insertion points. The punching of the material is accompanied by various physical processes at the insertion point (deformations, heating, melting, etc.), therefore it is performed at some distance from the cutting contour. The offset of the insertion point is defined relative to the equidistant of the original contour and coincides with the direction of the equidistant displacement (outward or inward of the contour).

For example, when processing an external contour with a waterjet machine, it is recommended to place insertion points only on convex corners of the contour formed by geometric primitives. In the case of processing the inner contour - on the contrary, the best place is in the center of the arc or segment. For a laser machine, the position of the tapping point can be arbitrary [1].

3. Direction of entry and exit. Entry and exit on the *i*-th equidistant is performed in the direction coinciding with the cutting direction, specified by parameter dir_i.

4. Start and end of TP. TP begins at the point P_{start} (usually, this is the origin of the coordinate system) and ends in point P_{end} (may coincide with P_{start}).

5. The order of contour processing. The order of contour processing must satisfy two constraints, called preconditions:

- processing of the external contour of a part can be carried out only after processing all of its internal contours;
- processing of parts embedded in the inner contour of another part must be made before the contour in which they are located.

To take into account the preceding conditions, the following rule is proposed. If there is an *i*-th contour inside the *j*-th contour $i \neq j$, then the *i*-th contour must be processed before the *j*-th contour, i.e.
$belongs(i,j) \Rightarrow cord_i < cord_j$,
where $belongs(i,j)$ – a predicate equal to *true* if the *i*-th contour belongs to the inner region of the *j*-th contour and false otherwise; $cord_i, cord_j$– number of the *i*-th contour and the *j*-th contour in the contour processing sequence.

Thus, a model for minimizing the total cutting time is constructed, taking into account constraints in the form of equidistant points, entry and exit points, preconditions and technologies of standard, chain and common cutting.

2.3 Basic stages of problem solving

To solve the task, it is necessary to perform a number of actions related to the preliminary stage:

1) construct a matrix of precedence conditions for contours [4];

2) determine the areas of the common cut on the nesting layout;

3) generate equidistant contours taking into account information about the common cut.

The obtained information will be used at the stage of TP optimization, which is also proposed to be divided into a number of actions:

1) generate a set of potential entry and exit points;

2) perform optimization of idle movement and stroking time, as well as the number of insertion

points. It should be noted that it is possible to minimize only the idle time.

2.4 Implementation features

Let's consider key implementation features of the general cut and equidistant accounting.

1. Common cut section determination. To use a common cut, groups of tightly laid parts with a common face are created. Because the contours are separated by a common cutting line, there is no need to cut the segment twice. A common straight line allows to place pieces at a distance *d*, which saves the material and reduces the total length of the cut. It should be noted that implementation of a general cut between arcs is not considered in this paper.

The admissibility of a common cut for a pair of geometric objects belonging to two different contours is determined by the fulfillment of a number of conditions:

1) both geometric objects are straight;
2) geometric objects are parallel to each other;
3) the lengths of geometric objects are equal;
4) none of the straight lines goes beyond the border of the other (aligned with each other);
5) the distance between geometric objects is equal to the cutting width *d*.

Determination of the common cut sections is performed between all pairs of contours. The geometric objects of these contours are compared in pairs with each other, and if all the TR are fulfilled, it is assumed that a common cut is allowed between the GO data. The complexity of the algorithm for determining sections of a common cut is $O(n^2)$, where *n* – is the total number of geometric objects on the nesting layout.

2. Equidistant alignment. A special situation occurs when it is necessary to construct an equidistant for a pair of combined contours. In this case, the following actions are performed:

1) construct equidistant [7] for all internal and external contours (Figure 1, a);
2) check whether the contours are aligned (that is, the conditions for a general cut are met);
3) if the contours are combined, combine the equidistant contours into one common equidistant (Figure 1, b).

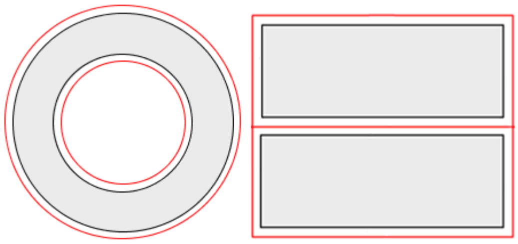


Figure 1: An example of simple equidistant for the inner and outer contours (a)
and a combined equidistant (b).

3 EXPERIMENTAL VERIFICATION OF THE MODEL

To verify the adequacy of the proposed model, we perform a numerical experiment using a nesting layout having several correct areas of the common cut. The experiment will also demonstrate the effect of a common cut on the cutting time.

The *ITAS Nesting* software complex is used as the environment for the experiment. As an algorithm for the formation of TP, the Great Deluge Algorithm is used, which gradually accomplishes the tasks of creating the sequence of parts machining and selecting insertion points on them. It should be noted that any other algorithm that allows to build a route taking into account technological limitations is suitable for using the model [8].

To determine the total cutting time, it is needed to know the cutting speed, idle speed and the time required for inserting the tool into the material. But since these parameters depend on the model of the machine, the type of material and its thickness, we use a special case of cutting a steel sheet of Russian St3 grade 50 mm thick.

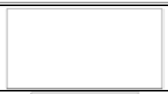
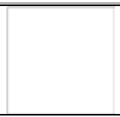
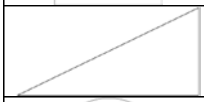
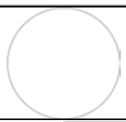
With this cutting, the following parameters are typical for the waterjet machine:

– the tool cutting speed is 25 mm / min.
– speed of tool idling - 1000 mm / min.
– material insertion time - 20 s.
– tool delay time before cutting starts - 3 s.

To test the effectiveness of the model, we will construct TP using general snake algorithm, original TP with and without common cutting (CC) for four different test cases (Figures 2-5).

First test case consists of 5 different parts packed in some irregular way. The content of this test case is presented in Table 1.

Table 1: Test case, 1 part.

Part	Width, mm	Height, mm	Count
	210,0	1050,0	2
	400,0	200,0	3
	200,0	200,0	2
	420,0	200,0	2
	100,0	100,0	2
	400,0	200,0	2

The aim of this test is to see how model will work on usual irregular nesting layout with basic parts. The layout is presented in Figure 2.

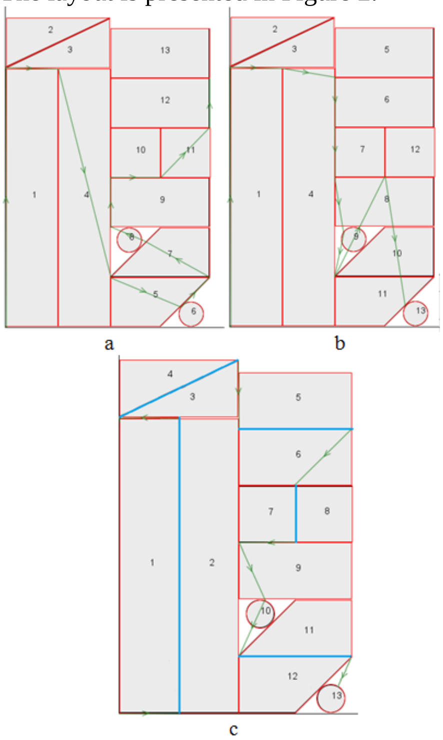
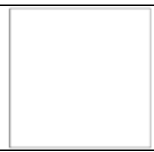
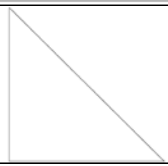


Figure 2: Test case 1 with default snake strategy (a), TP without use of common cut (b) and with it (c).

In Figure 2c, pairs of contours are processed by common cut: 1-2, 3-4, 5-6, 7-8, 11-12 (the common face is shown in blue). The contour numbers correspond to the order number of the processing.

Second test case consists of 3 different parts packed in pairs. The content of this test case is presented in Table 2.

Table 2: Test case, 2 parts.

Part	Width, mm	Height, mm	Count
	100,0	100,0	4
	200,0	100,0	2
	100,0	100,0	16

The aim of this test is to see total amount of profit provided by CC for nesting layout with high number of conjoined parts. The layout is presented in Figure 3.

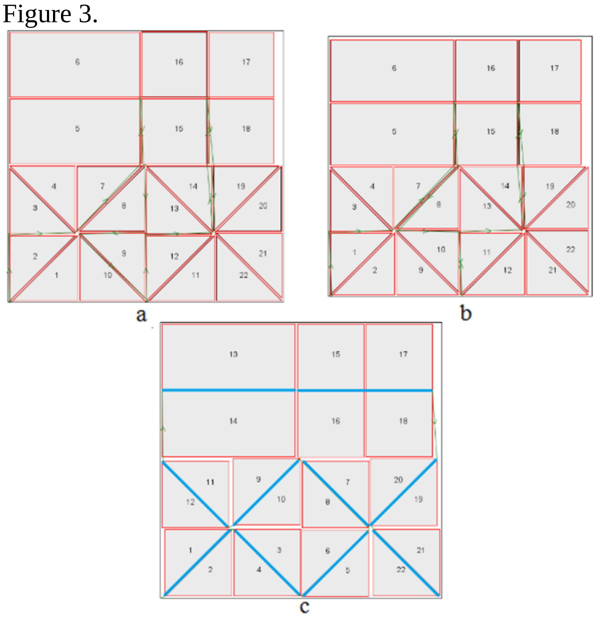
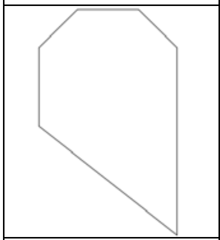
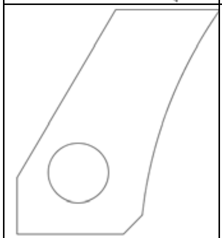


Figure 3: Test case 2 with default snake strategy (a), TP without use of common cut (b) and with it (c).

In Figure 3c, pairs of contours are processed by common cut: 1-2, 3-4, 5-6, 7-8, 11-12, 13-14, 15-16, 17-18, 19-20, 21-22. It may be noted that half of the parts were conjoined in this nesting layout.

Third test case consists of 2 different non-basic parts providing possible and impossible CC areas at the same time. The content of this test case is presented in Table 3.

Table 3: Test case, 3 parts.

Part	Width, mm	Height, mm	Count
	130,0	212,0	8
	53,5	60	19

The aim of this test is to see profit on complex parts with equal possible and impossible CC ratio for nesting layout square. The layout is presented in Figure 4.

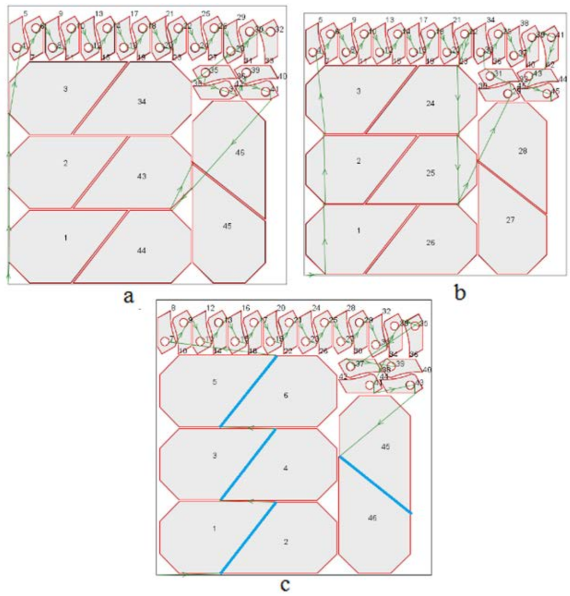
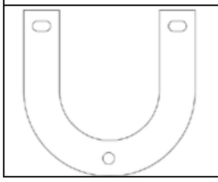


Figure 4: Test case 3 with default snake strategy (a), TP without use of common cut (b) and with it (c).

In Figure 4c, pairs of contours are processed by common cut: 1-2, 3-4, 5-6, 45-46. Most of the parts are not affected by CC.

Fourth test case consists of 1 part type packed in regular way without any CC possibility. The content of the test case is presented in Table 4.

Table 4: Test case, 4 parts.

Part	Width, mm	Height, mm	Count
	240,0	232,3	40

The aim of this test is to see if any profit can be achieved without CC on regularly nested parts since snake algorithm works best on such layouts. The layout is presented in Figure 4.

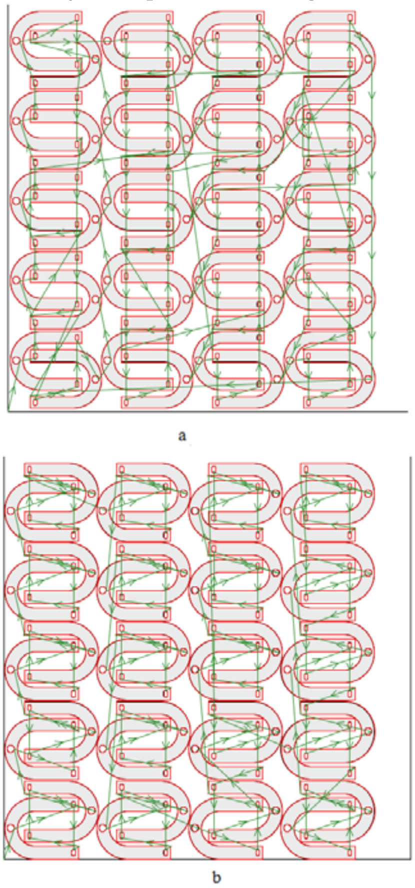


Figure 5: Test case 4 with default snake strategy (a), TP with and without use of common cut (b).

In Figure 4b, one can see that no parts were affected by CC.

The results of the experiment are summarized in Table 5. Default snake method is presented as absolute value while original TP is expressed as percentage difference to snake method.

Table 5: The results of a numerical experiment.

Parameter	Snake (value)	Without CC (percentage difference)	With CC (percentage difference)
Test case 1			
Idling (mm)	7133,0	22,2%	76,4%
Idling time (s)	428,0	22,2%	76,4%
Working stroke (mm)	15270,8	0,0%	16,5%
Working stroke time (s)	36649,9	0,0%	16,5%
Insertion points (pc.)	13	0,0%	38,5%
Insertion time (s)	299,0	0,0%	38,5%
Cutting time (s)	37376,9	0,3%	17,3%
Test case 2			
Idling (mm)	1546,0	0,1%	83,2%
Idling time (s)	92,7	0,1%	83,2%
Working stroke (mm)	8375,6	0,0%	19,2%
Working stroke time (s)	20101,5	0,0%	19,2%
Insertion points (pc.)	22	0,0%	50,0%
Insertion time (s)	506,0	0,0%	50,0%
Cutting time (s)	20700,2	0,0%	20,3%
Test case 3			
Idling (mm)	2050,5	5,1%	10,8%
Idling time (s)	123,0	5,1%	10,8%
Working stroke (mm)	9304,1	0,0%	7,4%
Working stroke time (s)	22329,9	0,0%	7,4%
Insertion points (pc.)	45	0,0%	8,9%
Insertion time (s)	1035,0	0,0%	8,9%
Cutting time (s)	23487,9	0,1%	7,4%
Test case 4			
Idling (mm)	32234,6	5,8%	5,8%
Idling time (s)	2114,1	5,8%	5,8%
Working stroke (mm)	64517,8	0,0%	0,0%
Working stroke time (s)	154842	0,0%	0,0%
Insertion points (pc.)	160	0,0%	0,0%
Insertion time (s)	3680,0	0,0%	0,0%
Cutting time (s)	23487,9	0,1%	0,1%

The numerical experiment showed a decrease in the total cutting time due to:

– the total idle movement time is slightly reduced for original TP without CC in range of 0,1-22%;

– the total idle movement time is greatly reduced (10,8-83,2%) for original TP with CC along with 7-19,2% reduction of working stroke;

– reduction of insertion time depends on count of conjoined parts and is up to 50% better for original TP with CC.

The decrease in the idling movements for the waterjet machine gives minor profit since its main time consumption is working stroke. It explains why original TP without CC gives only up to 0,3% total time profit. At the same time original TP with CC gives great time reduction up to 20% as in the test case 2 because of extremely low waterjet working speed.

It should be noted that best results can be achieved on irregular nesting layouts with high CC availability provided by conjoined parts with long straight lines. But even in the worst case, original TP is not worse than snake path giving some time profit on idle movement as 5,8% in the test case 4.

For further research, new tests with different idle/working speeds, including typical ones for laser machine, should be carried out. The difference between idle movement and idle stroke of laser machines is usually small since they work with thick materials [9]-[10]. Therefore, idle time reduction of around 80% as in the test cases 1 and 2 for CC, should give major total cutting time reduction.

4 CONCLUSIONS

As a result, the mathematical model of cutting time minimization has been developed. It differs from existing ones by:

– taking into account the technologies of standard, chain and common cutting;

– usage of equidistant contours, entry / exit points as technological limitations, conditions of contours and parts precedence.

The total cutting time is estimated taking into account the lengths of the equidistant, the lengths of the approaches / ejections and the types of transitions between equidistant contours (idle or working).

The numerical experiment carried out for the waterjet machine showed the adequacy of the constructed model. It is revealed that this model could give the results not worse than default snake strategy on regular nesting of complex parts, and up to 20% total cutting time decrease in high CC cases. Further research should be carried out, including laser machine modeling and introducing this technology in real industrial environment.

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