Optimized Sequencing Method of Machining Cells for Complex Structural Parts based on Process

Shulin Chen[1] and Min Zhou[2]

[1]Jinhang Digital Technology Co., Ltd., chensl@avic-digital.com
[2]China Agricultural University, zhoumin2016@cau.edu.cn

Corresponding author: Min Zhou, zhoumin2016@cau.edu.cn

Abstract. To solve the problem of the sequencing of machining cells in the automatic programming of large-scale complex structural parts, a process-based optimization sequencing method of machining cells is proposed. The method considers both the macro process layer and micro tool layer to realize the overall sequencing of large complex structural parts. First, at the macro process level, the processing cells are grouped into four levels according to the principle of real-time supplementary processing, and the sorting rules of the machining cells are established; secondly, for the machining cells associated with the tool, the simulated annealing algorithm is used to optimize the toolpath of the grouped cells, realizing the optimal sequencing of the machining cells in the entire CNC machining process such as procedures, steps, and tools. The result of the example shows that the proposed method effectively reduces the empty cutting, shortens the toolpath, and improves the efficiency of machining programming.

Keywords: Numerical control machining programming; Process; Machining cell; Sequencing; Simulated annealing algorithm
DOI: https://doi.org/10.14733/cadaps.2023.414-426

1 INTRODUCTION

Complex structural parts, such as aircraft structural parts, have the characteristics of many features, large size, and thin walls between adjacent pockets. In the manufacture of structural components for aircraft, process analysis and NC programming which were traditionally finished by human-computer interaction programming with universal CAM commercial software, such as CATIA and UG, usually consume more than 70% of the time required for the entire process for each new part[4]. The order of machining cells must meet the process requirements and ensure that the tool path is short to reduce the machining time. Therefore, the sorting of machining cells is a key link in the automatic programming of complex structural parts, and it is also a prominent and difficult problem. In order to improve the rough machining efficiency of complex parts, Zhang et al. [14] established a machining sequence optimization model, and used the tabu search algorithm to solve the model, but this method is only for independent features and cannot handle intersecting features. Zheng et al. [15] used a genetic algorithm (GA) to reconstruct the machining cell for the intersecting features of complex pockets. To improve the efficiency and quality of the process planning, Lian et al. [8] developed a multi-dimensional tabu search algorithm to optimize the four dimensions of a process plan, namely, operation sequence, machine sequence, tool sequence and tool approach direction sequence, sequentially and iteratively. Gao et al. [3] proposed an intelligent process planning method based on feature-based history machining data for aircraft structural parts. From the perspective of energy saving, Bi and Wang [1] optimize the machining processes by establishing the energy models based on kinematics and dynamics of machine tools with considerations on both the material flow and tool flow mutually. To optimize the operation sequence, Salehi and Bahreininejad [12] optimized the sequence of the operations of the part machine selection, cutting tool and TAD (tool approach direction) for each operation using the intelligent search and GA simultaneously. However, only the sequences of operations are optimized at the process level without consideration of the tool path optimization. In reference [7], to integrate the setup planning and operation sequencing problems for flexible manufacturing, technological constraints such as TAD, tolerance relation between features and feature precedence relations were analyzed to generate all possible setups and operations using workshop resource database. Then, the GA algorithm approach was adopted to simultaneously optimize the setup plan and sequence of operations using cost indices. Hu et al. [6] proposed a novel modified ant colony optimization algorithm considering constrained relationships among operations to optimize the sequence .Liu et al. [9] used configuration spaces to represent and analyze the machining effect and, through the iterative adjustment of the process scheme, updated and optimized the overall machining process; this method improves the efficiency of the process design but fails to give full consideration to machining parameters on the tool axis. For aircraft structural part, Xu et al. [13] proposed a chaotic simulated annealing algorithm to optimize the machining tool path of features with only one tool. Huang et al. [5] optimized the tool path by using a hybrid algorithm of ant colony optimization and tabu search for the process plan reuse problem of complex parts with intersecting features. In conclusion, most of the existing studies consider either macro process planning or only tool path optimization of the tool layer, and little research contribute to the overall sequencing of machining cell from both macro and micro levels. Therefore, this paper proposes a process-based optimization sequencing method for machining cells: at the macro level, the overall machining sequence is realized based on the process described by the process scheme; at the micro level, the sequencing of tool-related machining cells is emphasized. Finally, the sequencing method takes into all the key factors from the process to machining step and cutters, etc., in the entire CNC machining process.

2 THE PROCESS-BASED SEQUENCING METHOD

The technological process is the process of machining parts in the specified order according to the given working procedure, working step and process resources (cutters, machine tools, etc.) under the guidance of the process scheme. As shown in Figure 1, according to the technological process, the machining cells are ordered at the macro level and the micro level (cutter level). Among them, at the macro level, the macro process described by the process scheme is followed, including the machine tool to the cutter node; at the micro level, the machining cells associated with the cutters are grouped in multiple levels, and these cutter groups are sorted according to the technological process. Important definitions related to this paper in Figure 1 are as follows:

Working orientation: It indicates the fixed orientation of part on the table of machine tool. It also points out the machining side of the part.

Working procedure: It is the element of manufacturing process. It can also be defined concretely as a part of manufacturing process in which one part is machined during one machining phase on one work orientation of one machine tool.

Working step: It is a portion of working procedure process using one tool and cutting the same machining place.

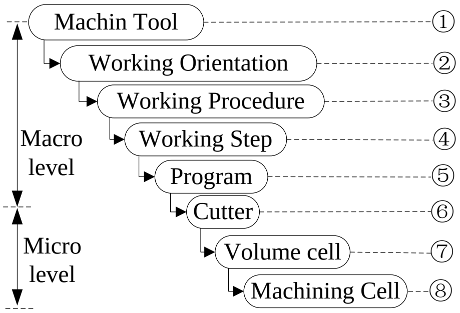


Figure 1: Sequencing hierarchy diagram based on process.

Volume cell: The material cell to be removed from the blank minus the part is decomposed to a series of independent basic three-dimensional area according to certain rules.

Machining cell: The smallest organizational structure in the CNC machining process formed by the combination of an operation unit and its selected machining operations (such as pocket machining, contour machining, iso-parametric machining, etc.) is called a machining cell.

Operation cell: The CNC machining tool path file of the CAM system is composed of several instantiated machining operations. The tool path generated by each machining operation can remove a certain three-dimensional area unit, which is called an operation cell.

2.1 Grouping of Machining Cells

As shown in Figure 2, according to a given process scheme, a set of tool sequences can be obtained, each cutter in the sequence is associated with a group machining cell, and this group of machining cells constitutes a "first-level group". In the first-level cell group, in order to make the part machining process meet the technology process requirements, the target machining cells and the real-time supplemented machining cells are separated to form a "second-level group". Since there are many types of supplemented machining cells, and different types of supplemented machining cells need to be processed in a centralized manner, the supplemented machining cells are grouped according to the type of working step to form a "three-level group". In addition, due to the special requirements of the process, some machining cells need to be grouped according to special process requirements. Take layered roughing as an example, the machining cells in each layer can form a group, a "four-level group".

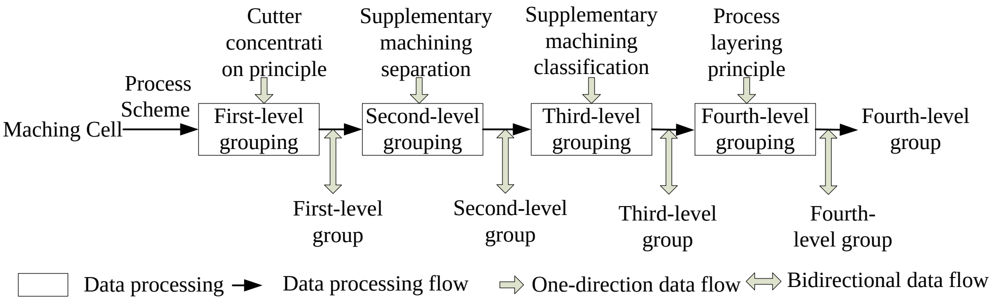


Figure 2: Grouping of machining cells.

The above grouping can be defined by the following model:

$$S=\bigcup_{1}^{m}S_1^i=\bigcup_{1}^{m}\bigcup_{1}^{n}S_2^{ij}=\bigcup_{1}^{m}\bigcup_{1}^{n}\bigcup_{1}^{h}S_3^{ijk}=\bigcup_{1}^{m}\bigcup_{1}^{n}\bigcup_{1}^{h}\bigcup_{1}^{b}S_4^{ijkl} \tag{2.1}$$

Among them, S is all machining cells, S_1^i is the machining cell group included in the i-th cutter in the given cutter sequence of the process scheme. S_2^{ij} is the j-th second-level cell group in S_1^i, which may be the target cell group or the supplementary machining cell group. S_3^{ijk} is the k-th third-level cell group in S_2^{ij}, which may be any working step type in the previous process. And S_4^{ijkL} is the l-th fourth-level cell group in S_3^{ijk} .Given machining c_1 and c_2, establish the following machining cell grouping rules:

First-level cell grouping rule: Let c_1 and c_2 use the tools t_1 and t_2 respectively, the machine tools are m_1 and m_2 respectively, the program segments are p_1 and p_2 respectively, the working steps are s_1 and s_2 respectively, the working procedures are r_1 and r_2 respectively, and the working orientations are o_1 and o_2, respectively. If $t_1= t_2$, $m_1= m_2$, $p_1= p_2$, $s_1= s_2$, $r_1= r_2$, $o_1= o_2$ are satisfied at the same time, then c_1 and c_2 belong to the same first-level cell group.

Second-level and third-level cell grouping rule: Given c_1 and c_2 belong to the same first-level cell group, and the main types are t_{m1} and t_{m2} respectively, and the working steps are t_{s1} and t_{s2} respectively. If $t_{m1}=t_{m2}$, then c_1 and c_2 belong to the same second-level cell group. In addition, if $t_{s1}=t_{s2}$, then c_1 and c_2 belong to the same type of real-time supplementary machining group, that is, the same third-level cell group.

Fourth-level cell grouping rule: Given c_1 and c_2 belong to the same third-level cell group, and their layers are l_1 and l_2 respectively. If $l_1 = l_2$, then c_1 and c_2 belong to the same fourth-level cell group.

According to the above rules, all machining cells can be classified into the four levels groups, which greatly reduces the complexity of the sorting and lays a solid foundation for the sorting based on the process.

2.2 Sequencing of Machining Cell Groups

After the machining cells are grouped, the machining cell groups are sorted based on the technological process. The rules are as follows:

Macro-sequencing rule: Let $S_1^1, S_1^2, \ldots, S_1^m$ be the initial sequence of all first-level cell groups and be disordered. According to the depth traversal of the process scheme, the processing sequence g_1, g_2, ..., g_m is obtained, in which the tool of g_i is t_i, the program is p_i, the working step is s_i, the working procedure is r_i, the working orientation is oi, and the machine tool is m_i, $1\le i\le m$. Set t_j is the cutter of machining cell group S_1^j, the program is p_j, the working step is s_j, the working procedure is r_j, the working orientation is o_j, and the machine tool is m_j. If $t_j=t_i$, $p_j=p_i$, $s_j=s_i$, $r_j=r_i$, $o_j=o_i$, $m_j=m_i$, then S_1^j should be placed in the i-th position of the new sequence, $j=1,2,\ldots,m$, and finally form a new first-level cell group sequence $S_1^{1'}, S_1^{2'}, \ldots, S_1^{m'}$.

Cutter-layer sequencing rule: Let the machine tool be m, the station be o, the working procedure be r, the working step be s, and the program to be p, the complementary machining cell group associated with the tool t_i is S_2^{i1}, the target cell group is S_2^{i12}, and S_2^{i1} can be divided into several initial sequences of the third-level cells $S_2^{i11}, S_2^{i12}, \ldots, S_2^{i1n}$, $1\le n$. Under the premise that the machine tool is m and the working orientation is o, the pre-procedure sequence of working procedure r is r_1, r_2, ..., r_l, $1\le l$, and the working step sequence of r_k is s_{k1}, s_{k2}, ..., s_{kh_k}, $h\ge1$, $1\le k\le l$. Under the working procedure r, the previous working step sequence of the working step s is s_1, s_2,

…, s_b. It can be seen that under the premise that the machine tool is m and the working orientation is *o*, the previous working step sequence of the working step *s* is $s_{11}, s_{12}, \dots, s_{1h_1}, s_{21}, s_{22}, \dots, s_{2h_2}, \dots, s_1, s_2, \dots, s_b$. Extract the working step type of the compensated machining of S_2^{i11} , S_2^{i12} ,…, S_2^{i1n} , and sorts S_2^{i11} , S_2^{i12} ,…, S_2^{i1n} in the order of $s_{11}, s_{12}, \dots, s_{1h_1}, s_{21}, s_{22}, \dots, s_{2h_2}, \dots, s_1, s_2, \dots, s_b$, generates a process-based supplemented machining sequence $S_2^{i11'}$, $S_2^{i12'}$,…, $S_2^{i1n'}$. Finally, add the target cell group S_2^{i12} to complete the process-based cutter-layer sorting.

2.3 Sequencing of Layered Machining

In order to reduce the roughing deformation, the structural parts usually adopt the layered roughing method. So, two layering methods, the overall layering and the virtual layering, are proposed to realize sequencing of layered machining.

2.3.1 Overall layering

From an overall perspective, the maximum height difference of all volume cell associated with the tool is the total height *h*, and the step distance s_a is used to divide *h* equally to generate the overall layer l_1, l_2, ⋯, l_m, $m \geq 1$. And, the machining cells associated with the tool are divided into layer interval $v_{i,i+1}$ (l_i, l_{i+1}) according to the *Z* coordinate value. Then, the four levels cell grouping is completed. In top-down order, if the machining cell satisfies $z_{l_i} < (z_{\omega t} + z_{\omega b})/2 \leq z_{l_{i+1}}$, assign the machining cell to layer interval $v_{i,i+1}$. Where, z_{l_i} and $z_{l_{i+1}}$ are *Z* coordinate values of layer surface l_i and l_{i+1}. As Figure 3 shows, according to the above method, the roughing cells are divided into four layer intervals, forming four fourth-level cell groups S_4^1 , S_4^2 , S_4^3 , S_4^4 .

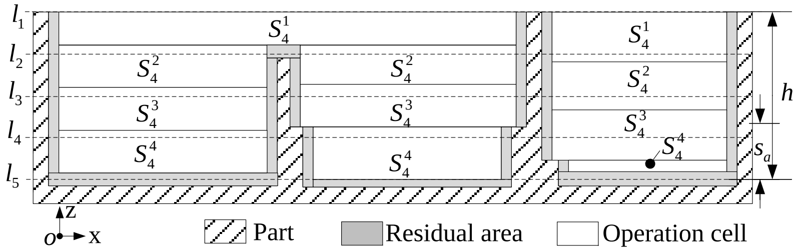


Figure 3: Roughing cells grouped by overall *layering method*.

2.3.2 Virtual layering

If the roughing tool can remove most of the volume cells, the overall layering has high machining efficiency with little deformation. However, when multiple tools are used for roughing, the volume cells that can be machined by each tool are less scattered, resulting in more paths without cutting at each level in the overall layering method, and lower efficiency. In order to reduce the invalid path and reduce the stress deformation of the side wall, the virtual layering is proposed. It is a virtual layer formed by concentrating laterally adjacent and axially intersecting machining cells. Among them, lateral adjacency means that there is a common thin-walled transition structure between the volume cells associated with machining cells, and axial intersection means that there is a certain overlap between the two machining cells in the axial height range, which can be expressed mathematically as $Range(z_{wb1}, z_{wt1}) \cap Range(z_{wb2}, z_{wt2}) \neq \emptyset$. Where, $Range(z_{wb1}, z_{wt1})$ is the axial machining range of machining cell c_1 while $Range(z_{wb2}, z_{wt2})$ is the axial machining range of machining cell c_2.As shown in Figure 4, four-level machining cell groups S_4^1, S_4^2, S_4^3, S_4^4, S_4^5, S_4^6, S_4^7 are obtained by grouping from top to bottom according to the virtual layering method.

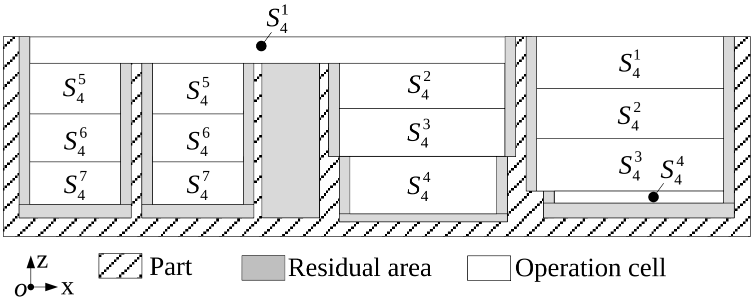


Figure 4: Roughing cells grouped by *virtual layering method*.

Regardless of overall layering or virtual layering, in general, the four-level cell groups are sorted in order from top to bottom, which conforms to the principle of layered roughing and avoids interference during machining.

3 OPTIMIZATION OF MACHINING PATH BY SIMULATED ANNEALING ALGORITHM

After the machining cell grouping and the sorting based on the technology process, the first to third level cell groups are all sorted on the process level. As the processing order of the machining cells in the fourth-level group has little correlation with the process, to reduce the useless path between machining cells, a simulated annealing algorithm is used to optimize the geometrical paths between machining cells.

3.1 Constraints

It is easy to know that the geometric features formed by a machining cell may affect the machining of other machining cells, that is, there are some machining sequence constraints in the process, such as clamping/positioning constraints. In addition, the machining of some cells may interfere with other machining cells, and there is a certain preferential machining relationship in geometry. Therefore, when the path is optimized, the corresponding process and geometric constraint rules are established in advance to ensure that the optimization results meet the actual process requirements.

3.1.1 Process constraints

Clamping/locating surface machining constraints: If the machining of machining cell c_1 would destroy the clamping or locating surfaces required by machining cell c_2, then c_2 should be processed first.
Datum first: If the geometric elements formed by the machining of machining cell c_1 are the datum required by machining cell c_2, then c_1 should be processed first.

3.1.2 Geometric constraints

For two machining cells c_1 and c_2 associated with any given cutter t, if the machining of c_2 will interfere with the operation cell of c_1, then c_1 should be processed first.

3.2 Optimization Model

The optimization model of the path among machining cells is defined as follows: (1) The tool path of a cell is defined as the tool path segment for the machining cell and its start and end points. (2)

The representation is the path between the machining cells and its solution space. (3) The solution target is the path optimization target. (4) The evaluation function, divided into closed-loop and open-loop, is used to evaluate the solution result. (5) The acceptance function is a function established according to the Metropolis probability acceptance criterion, used to decide whether to accept the new solution.

3.2.1 The tool path of a cell

After each machining operation is instantiated and the machining operation parameters are set, a tool path can be automatically generated. Therefore, each machining cell indirectly corresponds to a tool path, and its path is defined as follows: $L = f(p_c, p_{c_s}, p_a, p_r, p_{a_s}, p_{r_s}, l)$ .Where, p_c is the geometric center of the operation cell, p_a is the approaching point, p_r is the retract point, p_{c_s} , p_{a_s} and p_{r_s} are the points where p_c, p_a and p_r are projected to the safety plane along the axial direction, and l is the tool path segment.

3.2.2 Representation

The representation is a mapping from the state space of possible solutions to the state space of coded solutions under a specific data structure [10]. Given a four-level machining cell group $S_4=\{c_1, c_2,\ldots, c_n\}$, a sequence of machining cells $q(c'_1, c'_2, \ldots, c'_n)$, $c'_i \in S_4$, $1 \le i \le n$, is obtained according to a certain order rule, then, the sequence defines a path among machining cells. Since each machining cell is numbered, the ordering can be converted to a problem of arranging n positive integers, and the sequence of machining cells q is simply denoted as 1,2,…,n. Therefore, the path solution space can be expressed as $D = \{(i_1, i_2, \ldots, i_j, \ldots, i_n) | \ i_j$ is the number of the j-th element of the machining cell sequence$(c'_1, c'_2, \ldots, c'_n)$and $i_j \neq i_k,\ j \neq k,\ 1 \le j \le n,\ 1 \le k \le n\}$. Where, each sequence $(i_1, i_2, \ldots, i_n)$ represents a path among machining cells. The initial solution is set to (1, 2, ..., n), representing the initial sequence of paths as $c_1, c_2, \ldots, c_n$.

3.2.3 Solution Objective

Given a set of machining cells, with consideration of the process constraints and geometric constraints, find a shortest tool path along which all the machining cells are machined and each machining unit is machined only once. The mathematical description of this optimization goal for tool path among machining cells is as follows:

$$h(D) = \min \sum_{j=1}^{n} d(c_{i_j}, c_{i_{j+1}}) \tag{3.1}$$

Where, $d(c_{i_j}, c_{i_{j+1}})$ indicates the distance from the machining cell c_{i_j} to the $c_{i_{j+1}}$.

3.2.4 Evaluation Function

Given a feasible solution $q(i_1, i_2, \ldots, i_n) \in D$, the evaluation function is:

$$eval(q) = \sum_{j=1}^{n} d(c_{i_j}, c_{i_{j+1}}) \tag{3.2}$$

In the working steps of layered roughing, web finishing and internal and external contour finishing, the tool paths are generated by the profile operation with unknown approaching or retract points. Thus, the operation cell is simplified to a point, then a series of "single point" can be sorted to optimize the path of machining cells approximately. However, in the corner working step, the approaching and retract points can be calculated. Thus, the machining cell can be represented as a pair of points and a series of "double points" are optimally ordered. Besides, whether the starting machining cell is also the ending machining cell should be considered. If they are same, the path is called a "closed-loop", otherwise it is an "open-loop" path. Therefore, the evaluation functions of path optimization among single points and double points are established respectively:

1. "Single point" type

$$eval(q)=\begin{cases}\sum_{j=1}^{n-1} d(p_{c_s}^{i_j},p_{c_s}^{i_{j+1}}), & \lambda=0\\ \sum_{j=1}^{n-1} d(p_{c_s}^{i_j},p_{c_s}^{i_{j+1}})+d(p_{c_s}^{i_n},p_{c_s}^{i_1}), & \lambda=1\end{cases} \tag{3.3}$$

In Equation (3.3), $d(p_{c_s}^{i_j},p_{c_s}^{i_{j+1}})$ represents the distance from $p_{c_s}^{i_j}(x_{c_s}^{i_j}, y_{c_s}^{i_j}, z_{c_s}^{i_j})$ to $p_{c_s}^{i_{j+1}}(x_{c_s}^{i_{j+1}}, y_{c_s}^{i_{j+1}}, z_{c_s}^{i_{j+1}})$, Namely, $d(p_{c_s}^{i_j},p_{c_s}^{i_{j+1}}) = \sqrt{(x_{c_s}^{i_j}-x_{c_s}^{i_{j+1}})^2+(y_{c_s}^{i_j}-y_{c_s}^{i_{j+1}})^2+(z_{c_s}^{i_j}-z_{c_s}^{i_{j+1}})^2}$. Where, $\lambda=0$ if the path is an open-loop while $\lambda=1$ for the closed-loop. And the total length of the "closed-loop" path is $d(p_{c_s}^{i_n},p_{c_s}^{i_1})$ more than the "open-loop" path.

2. "Double points" type

$$eval(q)=\begin{cases}\sum_{j=1}^{n-1} (d'(p_{a_s}^{i_j},p_{r_s}^{i_j})+d(p_{r_s}^{i_j},p_{a_s}^{i_{j+1}}))+d'(p_{a_s}^{i_n},p_{r_s}^{i_n}), & \lambda=0\\ \sum_{j=1}^{n-1} (d'(p_{a_s}^{i_j},p_{r_s}^{i_j})+d(p_{r_s}^{i_j},p_{a_s}^{i_{j+1}}))+d'(p_{a_s}^{i_n},p_{r_s}^{i_n})+d(p_{r_s}^{i_n},p_{a_s}^{i_1}), & \lambda=1\end{cases} \tag{3.4}$$

In Equation (3.4), $d(p_{r_s}^{i_j},p_{a_s}^{i_{j+1}})$ represents the distance from $p_{r_s}^{i_j}(x_{r_s}^{i_j}, y_{r_s}^{i_j}, z_{r_s}^{i_j})$ to $p_{a_s}^{i_{j+1}}(x_{a_s}^{i_{j+1}}, y_{a_s}^{i_{j+1}}, z_{a_s}^{i_{j+1}})$, Namely, $d(p_{r_s}^{i_j},p_{a_s}^{i_{j+1}}) = \sqrt{(x_{r_s}^{i_j}-x_{a_s}^{i_{j+1}})^2+(y_{r_s}^{i_j}-y_{a_s}^{i_{j+1}})^2+(z_{r_s}^{i_j}-z_{a_s}^{i_{j+1}})^2}$. Where, $d'(p_{a_s}^{i_j},p_{r_s}^{i_j})$ represents the length of the tool path section from point p_{a_s} to point p_{r_s}. Obviously, $d'(p_{a_s}^{i_j},p_{r_s}^{i_j})$ is a constant and is set as g_{i_j}, then Equation (3.5) can be established:

$$eval(q)=\begin{cases}\sum_{j=1}^{n-1} (g_{i_j}+d(p_{r_s}^{i_j},p_{a_s}^{i_{j+1}}))+g_{i_n}, & \lambda=0\\ \sum_{j=1}^{n-1} (g_{i_j}+d(p_{r_s}^{i_j},p_{a_s}^{i_{j+1}}))+g_{i_n}+d(p_{r_s}^{i_n},p_{a_s}^{i_1}), & \lambda=1\end{cases} \tag{3.5}$$

3.2.5 Accept function

To evaluate the superiority of the new solution generated by the iteration of the algorithm compared to the initial solution of the iteration, the cost difference calculated for the *i*-th path optimization iteration is established as $\Delta eval_i = eval(q_i^{'})-eval(q_i)$. Where, $\Delta eval_i$ is the difference of the total length of paths generated before and after the *i*-th iterations, while q_i is the initial solution of the *i*-th iteration and $q_i^{'}$ is the new solution generated by the *i*-th iteration. According to the simulated annealing algorithm, the acceptance function is established by the Metropolis probabilistic acceptance criterion:

$$q_{i+1} = \begin{cases} q_i^{'}, & \Delta eval_i < 0 \,||\, \exp(-\Delta eval_i / t_k) > random(0,1) \\ q_i, & \Delta eval_i == 0 \,||\, (\Delta eval_i > 0 \,\&\&\, \exp(-\Delta eval_i / t_k) <= random(0,1)) \end{cases} \quad (3.6)$$

Where, t_k is the temperature during annealing, and *random*(0,1) is a function of producing random decimals between 0 to 1.

3.2.6 Neighborhood

Define a mapping *f*: $D \rightarrow 2^d$ which means a neighborhood *D*or that any point $x \in D$ in the search space *D* is defined*.* In this paper, a 2-transform mapping is adopted. Then, a series of new potential solutions are generated by a solution x. That is, two machining cells are randomly selected in the current solution firstly, and then the machining cells and machining cells between them are sorted in reverse order. The processing path formed by this operation is the neighborhood under the action of the 2-transform operator, which is mathematically defined as D' = $\{x \in D|\ x$ is obtained by a 2-transformation of y, $y \in D\}$. Obviously, the scale of the 2-transformed neighborhood is: $|D'| = (n-1)(n-2)/2$.

3.3 Algorithm

3.3.1 Algorithm flow

The simulated annealing algorithm flow is as follows:

Step 1: Define and initialize the cooling progress parameters(start and end temperature of annealing t_s and t_e, attenuation coefficient σ, and chain length L_k), the number of times *s* that the solution in the Mapkob chain length has no change, and the initial solution q_0;

Step 2: Repeat Step3 to Step5 for the current annealing temperature t_k and the number of iterations i=1, 2, …, L_k;

Step 3: Transform the initial solution q_i of the current iteration to randomly generate its new solution $q_i^{'}$;

Step 4: Calculate the function cost difference $\Delta eval_i$;

Step 5: Determine whether to accept the new solution according to the acceptance function, if accepted, set q_i+1=$q_i^{'}$, otherwise q_i+1=q_i;

Step 6. After L_k iterations, perform annealing to cool down;

Step 7: If the iteration termination condition is met, output the current optimal solution and end the program. Otherwise, return to Step2 and continue the iterative calculation. When there is no change in the solution in the length of several adjacent Mapkob chains, the iteration is exited.

3.3.2 Parameters selection

The cooling schedule is a set of parameters that control the progress of the algorithm. It is used to approximate the asymptotic convergence process of the simulated annealing algorithm. Selecting a reasonable cooling schedule is very effective to improve the quality of the optimization while minimizing the CPU running time. Its main parameters are: initial temperature t_0, attenuation function of temperature, Mapkob chain length L_k and stopping criterion.

According to the example of the machining unit of aircraft structural parts, several experiments are carried out to select reasonable parameters to realize the path optimization of the machining unit quickly and with high quality. The key control parameters meet the following requirements: (1) The adopted attenuation function are: $t_{k+1} = \sigma t_k$, k=0, 1, 2,... ; (2) The Mapkob chain length is determined as an integer multiple of the problem size n; (3) The stopping criterion is determined as the algorithm stops when the solution is no change in a s=1 adjacent Mapkob chain length.

Simulated annealing experiments were performed for given different values of t_0, σ, and L_k. The orthogonal test method is adopted. With comprehensively consideration of the quality of the final solution and the calculation efficiency, the final determination of $t_0 = 200$, $\sigma = 0.8$, and $L_k = 50$ meets the optimization sorting requirements in the automatic programming process.

4 ALGORITHM AND IMPLEMENTATION OF MACHINING CELLS OPTIMAL SEQUENCING

4.1 Algorithm

The flow of the process-based optimized sequencing algorithm for machining cells is shown in Figure 5.

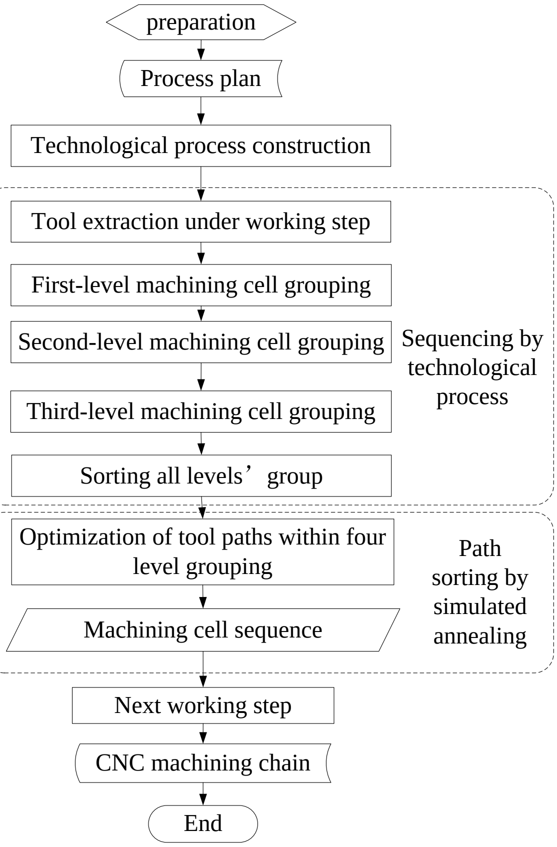


Figure 5: The flow of optimized sequencing of machining cells based on process.

Step 1: Input the process plan file, the plan is stored in the form of a tree structure in xml format;

Step 2: Deeply traverse the process plan structure tree to form the macro technological process of part machining, obtaining the tool serials t_1, t_2, ..., t_n, $n \geq 1$;

Step 3: According to the principle and method of automatic construction of machining cell [2], the machining cell of each tool is constructed. Then, and the first-level cell grouping at the tool level is realized according to the first-level machining cell grouping rules;

Step 4: In the first-level cell group, the machining cells are divided into the supplementary machining cell and the target machining cell to realize the second-level cell grouping. And the supplementary machining cell group are arranged before the target machining cell group;

Step 5: In the second-level cell group, the cells are divided into several third-level cell groups according to the type of working step. The third-level cell groups are further sequenced based on the technological process;

Step 6: In the third-level cell group, cells are divided into fourth-level cell groups according to the process requirements. And the tool path for the cells machining in fourth-level cell group is optimized by the simulated annealing algorithm.

Step 7: According to the above method, the machining cell sequence of each tool is obtained and integrated with the machining plan to form the final CNC machining chain.

4.2 Implementation and Verification

Applying the above-mentioned sequencing methods and algorithms, the module "optimized sequencing of CNC machining cells" has been developed, which has been applied to the rapid programming for many aircraft structural parts. The tests are given as an example in the following to verify the effectiveness of the algorithm.

As shown in Figure 6, it is a typical aircraft rib part which includes 78 pockets, 312 corners, 64 webs, and 12 openings. The process plan mainly includes two working procedures: (1) Rough machining: the tool is Φ32 with r3.2, the radial allowance is 2mm, and the axial allowance is 1mm. (2) Finishing: it consists of web machining, corner machining and internal and external contour working steps. Where, the web machining tool is the same as the rough machining with the axial allowance 0mm. And the corner and internal and external contour finishing use the tool Φ 16withr3.2 when both radial and axial allowances are 0mm.

Under the premise of a given process plan, after the machining cells are sequenced based on the process with machining operations instantiated, the machining tool paths of each working step generated in the CATIA CNC machining module are shown in Figure 7. Among them, the dotted line is the transitional connection tool path between the machining cells. The shorter the total length of the dotted lines, the less time it takes to pass idle path. It can be seen from the example that the proposed sequencing method based on the technological process conforms to the actual technological process and meets the technological requirements, and realizes the optimization of the tool path, which significantly improves the program quality and machining efficiency.

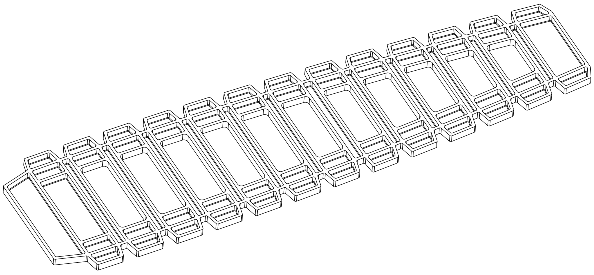
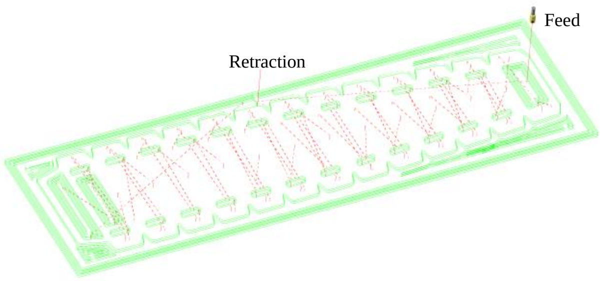
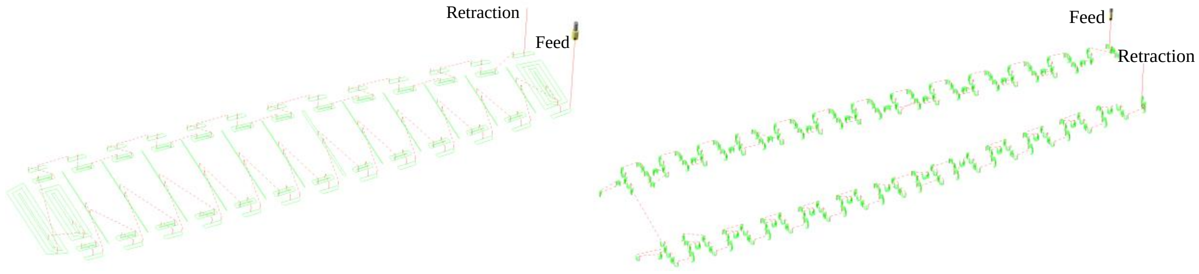


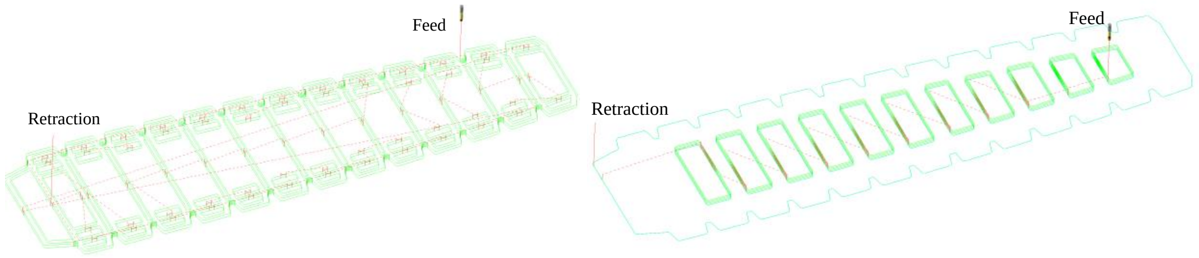
Figure 6: An aircraft rib.



(a)



(b) (c)



(d) (e)

Figure 7: Optimal sequencing results of machining cells reflected by toolpaths: (a) roughing: overall Layering + random sorting, (b) web machining: simulated annealing optimization, (c) corner machining: simulated annealing optimization, (d)internal and external contour machining: corner supplementary machining+ simulated annealing optimization, and (e) cutting machining: simulated annealing optimization.

5 CONCLUSIONS

Machining cell sequencing is one of the key links and core technologies in CNC programming. Most of the existing research focused on the process planning and machining feature sequencing, which is difficult to meet the process requirement. In this study, a process-based optimization sequencing method of machining cells is proposed. This method comprehensively considers the macro-process flow and the sorting in the working steps, and effectively integrates the sequencing of the process level and the geometric level. It is mainly divided into macro level (process level) and micro level (cutter level). In the macro level, the machine tool, working orientation, working procedure, working step, program and tool node are sorted based on the technological process described by process. And in the micro level, the tool-related machining cells are grouped in four levels firstly. Then, the machining cell groups in a same level are sorted based on the technological process, while the tool paths among machining cells in a group are optimized by simulated annealing algorithm. Finally, the algorithm is developed and implemented to verified the validation of the proposed method. The sequencing results meet the process requirements, which can effectively reduce interference and over-cutting in the machining process, with short machining path and high efficiency.

Shulin Chen, https://orcid.org/0000-0001-8275-5623
Min Zhou, https://orcid.org/0000-0002-8569-5846

REFERENCES:

[1] Bi, Z.-M.; Wang, L.-H.: Optimization of machining processes from the perspective of energy consumption: A case study, Journal of Manufacturing Systems, 31(4), 2012, 420-428. https://doi.org/10.1016/j.jmsy.2012.07.002

[2] Chen, S.-L.; Zheng, G.-L.; Zhou, M.; Du, B.-R.; Chu, H.-Z.: Process-scheme-driven automatic construction of NC machining cell for aircraft structural parts, Chinese Journal of Aeronautics, 26(5), 2013, 1324-1335. https://doi.org/10.1016/j.cja.2013.07.035

[3] Gao, X.; Mou, W.-P; Peng, Y.: An Intelligent Process Planning Method Based on Feature-based History Machining Data for Aircraft Structural Parts, Procedia Cirp, 56, 2016, 585-589. https://doi.org/10.1016/j.procir.2016.10.115

[4] Harik, R.-F.; Derigent, W. -E.; Ris, G.: Computer aided process planning in aircraft manufacturing, Computer Aided Design and Application, 6(5), 2008, 953 - 962.http://doi.org/10.3722/cadaps.2008.953-962

[5] Huang, B.; Zhang, S.-S.; Huang, R.; Li, X.-L.; Zhang, Y.-J.; Liang, J.-C.: An Effective Numerical Control Machining Process Optimization Approach of Part With Complex Pockets for Numerical Control Process Reuse, IEEE Access, 7, 2019, 45146-45165.https://doi.org/10.1109/ACCESS.2019.2908877

[6] Hu, Q.-W; Qiao, L.-H; Peng, G.-W: An ant colony approach to operation sequencing optimization in process planning, Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture, 231(3), 2015, 470-489. https://doi.org/10.1177/0954405415616786

[7] Kafashi, S.: Integrated setup planning and operation sequencing (ISOS) using genetic algorithm, The International Journal of Advanced Manufacturing Technology, 2011, 56.5: 589-600.https://link.springer.com/article/10.1007/s00170-011-3202-0

[8] Lian, K.-L; Zhang, C.-Y; Shao, X.-Y; Zheng, Y.-H: A multi-dimensional tabu search algorithm for the optimization of process planning, Science China Technological Sciences, 54, 2011,3211–3219. https://doi.org/10.1007/s11431-011-4594-7

[9] Liu, X.; Li, Y.-G.; Tang, L.-M.: A dynamic feature–based operation planning method for 2.5-axis numerical control machining of complex structural parts, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 2015, 229.7: 1206-1220.https://doi.org/10.1177%2F0954405414560621

[10] Michalewicz, Z.; Fogel, D.-B: How to Solve it: Modern Heuristics, Springer, Enlarged 2nd edition, 2013.

[11] MUSHARAVATI, F.; HAMOUDA, A.-M.-S.: Simulated annealing with auxiliary knowledge for process planning optimization in reconfigurable manufacturing, Robotics and Computer-Integrated Manufacturing, 2012, 28.2: 113-131. https://www.sciencedirect.com/science/article/pii/S0736584511000950

[12] Salehi, M.; Bahreininejad, A.: Optimization process planning using hybrid genetic algorithm and intelligent search for job shop machining, Journal of Intelligent Manufacturing, 22, 2011, 643-652.https://doi.org/10.1007/s10845-010-0382-7

[13] Xu, J.-L.; Zheng, G.-L.; Du, B.-R.; Chu, H.-Z.; Wu, F.-M.: Mathematical model and algorithm of toolpath optimization on aircraft structural parts, International Journal of Production Research, 52(4), 2014, 1142-1149. https://doi.org/10.1080/00207543.2013.842022

[14] Zhang, C.-W.; Han F.-Y.; Zhang W.: A cutting sequence optimization method based on tabu search algorithm for complex parts machining, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 233(3), 2019, 745-755.https://doi.org/10.1177/0954405417752527

[15] Zheng Z.-J.; Wang, Q.-S.; Zheng, G.-L.; Zhu, J.-B.: An optimal approach to manufacturing planning for complex prismatic parts with interacting feature, The International Journal of Advanced Manufacturing Technology, 94(1), 2018, 585-597.https://doi.org/10.1007/s00170-017-0865-1