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ASUPPA: A FRAMEWORK FOR INTERACTIVE AND ITERATIVE SYNTHESIS AND IMPROVEMENT OF PROCESS PLANS

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ABSTRACT

The limited success and acceptance of automated process planning methods in the industry can be traced to the fact that most existing approaches aim at complete automation. We believe that the quest for complete automation is flawed, both because in practice optimality metrics for process plans are context-sensitive, and because there is significant organizational resistance to approaches that completely eliminate humans from the process planning framework. In this paper, we present an interactive and iterative planning framework, called ASUPPA, which focuses instead on providing intelligent assistance to a human process planner. After generating a "good" default process plan, ASUPPA engages in a "present – elicit criticism – revise" loop with an expert process planner. To operate successfully, ASUPPA needs access to the full search space of process plans, and have the ability to incrementally modify plans in response to expert criticism. The former is provided by basing ASUPPA on ASU Features Testbed, a comprehensive and systematic framework for recognizing and reasoning with features in machinable parts. To support the latter, the system is equipped with an iterative and interactive search mechanism. We will discuss the operational details of the resultant system, called ASUPPA

1 INTRODUCTION

Computer-aided process planning (CAPP) is a key part of bridging the link between design and manufacturing (Shah 1995). Process planning involves determining the sequence of operations to perform to manufacture a part given its description and the specification of the resources in the workshop. While the early approaches to process planning were pre-dominantly manual and provided at best database support for process planning (e.g., variant process planning), most recent approaches have (e.g. (Britanik, 1995; Gupta, 1994; Hayes, 1996; Kambhampati, 1993)) aimed for full automation by searching for a plan that is optimal with respect to a pre-specified objective function. If the predominantly manual older approaches were under-ambitious in exploiting the computer technology, the newer methods that aim at full automation are over-ambitious for at least three reasons:

- The search space for process plans is too large to facilitate an efficient systematic search. This often necessitates restricting focus to a single interpretation of current design and finding the best plan under this fixed feature set(which may not be the best plan globally).
- Second, and perhaps more important, these approaches assume the availability of a pre-specified objective function for evaluating process plans. In reality, the evaluation metrics for process plans are very much context dependent, and it is rarely the case that an accurate optimality metric is available a priori. Moreover, the user may change the optimality criteria for the process planning during the process of finding an optimal solution.
- A third and related shortfall of the current approaches is that they attempt at full automation in a situation where organizations are not comfortable delegating full process planning responsibilities to a computer. [2]

What is needed is an approach that provides more intelligent support for process planning than is provided by approaches

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[2] Prof. Mantyla, a prominent process planning researcher, relates an anecdote about how when his research group offered their state-of-the art process planning system for use in a Finnish company, the company politely refused saying that process planning is too important an activity to be entrusted solely to a program.

like variant planning (that mostly concentrate on indexing and retrieval), but do provide a significant role for the planning expert to *steer* the planner towards more desirable solutions. To overcome these limitations, we present a interactive and iterative plan improvement framework called ASUPPA[3], which is designed to *help* the human process planner in coming up with process plans. After generating an initial default process plan, ASUPPA engages in a "present – elicit criticism – revise" loop with an expert process planner. In contrast to approaches like variant planning, ASUPPA has access to the full search space of the process plans, and is able to understand the dependencies between the various parts of a process plan and approaches for revising them. In contrast to pure generative approaches, ASUPPA is designed bottom-up with the expectation that planning involves a significant amount of interaction with the user, and the consequent revision of the initial solution.

Designing such an intelligent process planning assitant however presents several technical challenges that subsume many of those present in designing generative planners. More specifically, our planner not only needs the ability to generate default process plans, it also needs to support structured interaction with the expert human process planners to elicit a criticism of its process plan. Finally, it needs the ability to continually revise candidate process plans in response to the criticism.

The task level architecture of ASUPPA is shown in Figure 1 (Li, 1997). The intended user is an experienced human process planner, who is expected to be knowledgeable both about the products and about the manufacturing facilities of the factory. The planner starts with a default optimality metric (which can be seen as the part of the expert quality metric that has already been articulated), and incrementally generates a process plan. To provide access to the complete search space of candidate process plans, we implement ASUPPA on top of the ASU Features Testbed (ASUFTB), a comprehensive and systematic framework for recognizing and reasoning with features in machinable parts.

The default process plan is then presented to the expert for critique. To support structured interaction with the user, we use a default parametric theory of plan quality. The expert rates the various quality parameters of the presented plan, and the parameters getting lower ratings are seen by ASUPPA as opening avenues for plan improvement.

In order to incorporate the criticism and improve the plan, ASUPPA uses a qualitative theory of the dependencies between the quality parameters and the parameters of the plan itself (such as the reference features used, the maching order, the processes used etc.). These dependecies are then used to decide which aspect of the plan needs to be modified to provide the most improvement in the quality rating. Depending on the part of the plan that needs to be revised, there are specific "fixes" for carrying out the revision. These fixes can be seen as ways of "renavigating" the search space of process plans. These fixes can be as simple as swapping a process with another (such as drilling with milling), or as involved as locally re-interpreting the part in terms of an alternative set of machinable features. Once the fixes are applied to the plan, ASUPPA has a new candidate plan, which it then iteratively improves and presents to the expert for further criticism.

Both the search for the initial default plan, as well as the revision of the plan in response to user criticism is done within an iterative local search regime (Rabideau, 1999; Zweben, 1994). The local search regime is particularly appropriate for our purpose as it naturally supports iterative nature of the planning episode (with some search iterations being driven by the system itself, while others being motivated by external expert-criticism). The local search also provides the much needed stability between iterations. Specifically, the search process attempts to keep the parts of the plan unaffected by the user criticism unchanged between consecutive interaction episodes, so as to provide the expert a reasonable reference frame for evaluating the improvements.

Using ASUPPA for generating process plans thus frees a human process planner from the nitty-gritty of search space navigation, while offering the luxury of not having to completely articulate the optimality metrics *a priori*. The expert need only provide criticisms on the quality of the process plan that is presented, leaving the details of plan revision to the program.

The rest of the paper provides the details of ASUPPA architecture and implementation. Section two briefly reviews the ASUFTB framework. Section three provides an overview of ASUPPA approach. Section four describes the parametric theory of plan quality used by ASUPPA. Section five discusses the dependencies between the quality parameters and the operational features of the plan. Section six presents the detailed steps involved in default plan generation. Section seven describes how ASUPPA structures the expert's critique of its plan. Section eight describes how the user criticisms are used to (re)navigate the plan search space. This section also discusses the strategies used to handle the interactions among the criticisms if the expert provides multiple criticisms of the plan. Section nine studies an example to demonstrate the capability of the planning system. The paper is finally summarized in section ten which describes the related research and future work.

2 ASU FEATURES TEST BED (ASUFTB)

As mentioned earlier, ASUPPA's knowledge about process plans is derived from the ASU Features Test Bed (ASUFTB), which is developed by Shah et al. (Shah, 1994). ASUFTB is a design by feature system and can systematically enumerate alternative features and machining interpretations for an object, assuming most discrete machining processes produce non-concave removal volumes as much as possible in a single setup. So the

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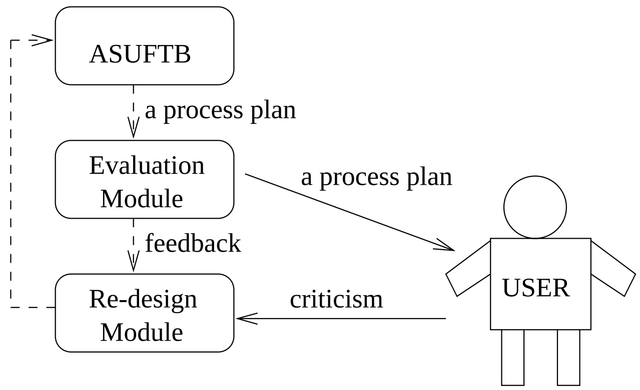

Figure 1. THE ARCHITECTURE OF ASUPPA

machining feature to be removed in a single setup should be maximally convex. We will now briefly describe the operation of ASUFTB with the help of the system structure illustrated in Figure 3 bounded by the dashed line.

The feature_based design modeller is used to describe the given part and its stock. The decomposer decomposes the total volume to be removed by machining, called as total removable volume (R) obtained by subtracting the part (P) from the stock (S), into minimum convex cells called atomic cells using a method called "halfspace partitioning" (Shah, 1994). Every atomic cell produced by halfspace partitioning is assigned a vector called a HalfSpace Vector (HSV). The composer combines these atomic cells into various machining feature sequences according to their HSVs. Every machining feature sequence is an input to the process selector where process selection is done for individual features in the sequence on the basis of shape capability of the process (shirur, 1994). Therefore, support for process planning in ASUFTB comes at two different levels. First called the "sequence level" involves splitting the removal volume into atomic cells, combining them into various machining feature sequences. Second, called the "process level" involves picking feasible machining processes for each of the features in the chosen feature sequence. Thus, ASUFTB implicitly sets up the search space consisting of all possible feature sequences for machining the part. The role of ASUPPA is to expand and navigate this search space guided by the evaluation metrics and the user feedback.

3 APPROACH OVERVIEW

3.1 Search Space Setup by ASUFTB

ASUPPA begins its operation based on the search space set up by ASUFTB, which is illustrated in Figure 2. Each feature sequence, Fea_seq1, Fea_seq2,.., and Fea_seqm, is an ordered list of machining features. Two feature sequences might consist of same features, but in a different order.

Each feature sequence can be seen as a node to be expanded since if it is input to process selector module, multiple various process plans can be generated. However, to narrow the size of the search space and speed the process of good process plan generation, our planning system expands a feature sequence node until it becomes necessary (see definition below). Therefore, before our process planning system is to be applied, the search space set up by ASUFTB is a space of feature sequences. Some nodes (the worst case, all the feature sequence nodes) in the space will be gradually expanded when the planning process applies.

A feature sequence node becomes necessary to be expanded when the heuristic function defined in the planning system determines the feature sequence as the most desirable direction to find a good process plan, or when the user criticisms given to the current process plan are mapped to the feature sequence.

The heuristic function defined in the sequence level to pick up a desirable feature sequence in the planning system is to calculate the total penalty cost of the feature sequences. The lower the total sequence level penalty cost for a feature sequence, the better its quality. The heuristic function defined in the process level to choose a good plan with respect to the specified sequence is to calculate the total penalty cost of process plans. The lower the cost of a process plan, the more likely that it has the better quality (see Section six for more details about penalty cost calculation).

After ASUFTB implicitly sets up the search space consisting of all possible machining feature sequences, the objective of our approach is to generate a good process plan by gradually expanding feature sequences by inputting them into the process selector module when it proves to be necessary by the evaluation metrics and the user feedback.

3.2 System Overview

The detailed idea of the system is given in Figure 3. The system can be considered as consisting of two loops, inner loop and outer loop. Figure 1 uses dashed line to denote the innner

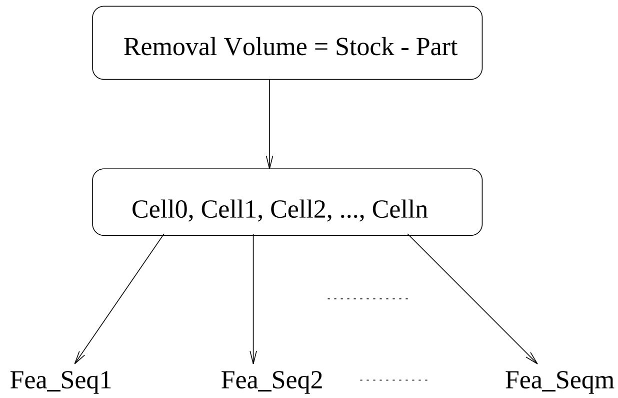

Figure 2. Process Plan Search Space Setup By ASUFTB

loop and the solid line to represent the outer loop. The inner loop attempts to find a local optimal plan in the sense that the plan coming from inner loop is optimal with respect to the default criteria in the planning system. The outer loop will take the output of the inner loop, and the user's feedback, to find a process plan that satisfies the user. Therefore, the process planning system becomes a semiautomatic system and the user and the evaluation module steers the improvement direction from case to case (Li, 1997). The real issues in applying this approach are learning the user's expectation about the plan and operationalizing the user criticisms as advice about how to navigate the search space of possible plans.

More specifically, the approach involves the following steps:

- Step 1. For a given part, evaluate all corresponding feature sequences using sequence level quality parameters, and pick up all sequences which have the lowest sequence level penalty cost and zero accuracy penalty cost (see section 4 for explanation of accuracy parameter). Suppose such a set is called FS.
- Step 2. Input a feature sequence $S \in FS$ into the process selector module, generate a set P of all possible process plans for S.
- Step 3. Evaluate each process plan in P using process level quality parameters, pick up one with minimum process level penalty cost and zero feasibility penalty cost (see section 4 for explanation of feasibility parameters), and determines whether there is any more improvement that can be done. If there is, a new feature sequence is chosen from FS (Section 6 gives details about why and how to choose a new feature sequence from FS), and step 2 is repeated. Otherwise, the plan is presented to the user.
- Step 4. If the user is satisfied with the plan, programs exit with success. Otherwise, it continues on to step 5.
- Step 5. Ask the user to critique the plan. Map the criticisms to different levels of the search space to make a new seed plan, and go back to Step 4.

After step 3, the planning system expands some feature sequences and the search space becomes as shown in Figure 4. The plan presented to the user is called a default plan with minimal process level cost with respect to a feature sequence with minimal sequence level cost.

In order to implement this approach, we need to structure the interaction between the planner and the user, and also determine the details of the planner's iterative search process. In particular, we need to answer the following questions:

- How should plans be evaluated?
- What is the relationship between the properties of a plan and plan improvement?
- How should a default plan be generated?
- How to structure the interaction with the user ?
- How should the interactions between the criticisms be handled by ASUPPA?
- How can the planning system learn the user's expectation about the plan?

4 PROCESS PLAN EVALUATION

A plan is evaluated at two levels: sequence level and process level (Hirode, 1996). The feedback information is a value that indicates the deviation from a target and is used to calculate the penalty cost of the plan.

There are three sequence level quality parameters: accuracy, consistency and air time.

- Accuracy parameter
  It checks whether the referenced feature is machined first.
- Consistency parameter
  It measures the ability of process plans to repetitively produce parts within the specified tolerances.
- Air time parameter
  It evaluates the air time, the time when no cutting is done but the tool is being moved from one position to another.

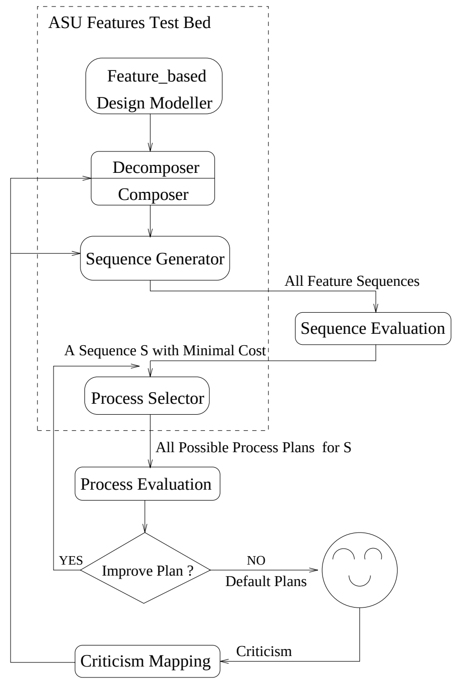

Figure 3. Process Planning System Flowchart

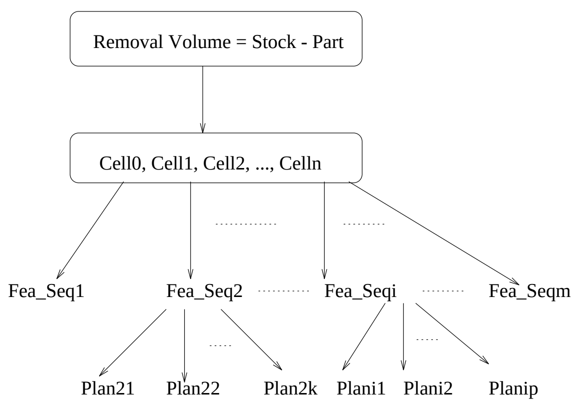

Figure 4. Process Plan Search Space After Expanding Some Feature Sequence Nodes

In process level evaluation, feasibility, accuracy, consistency, machining time and number of setups are used as quality parameters. This evaluation level looks at how good a process is to produce the individual feature. Although accuracy and consistency have the same name as they have in sequence level evaluation, the focus is different.

- Feasibility parameter
  The size capabilities of processes are compared with the intrinsic dimensions of features and checked whether they are feasible candidates for machining the feature volume.
- Accuracy parameter
  It checks whether the assigned processes meet the form and finish specifications.
- Consistency parameter
  It focuses on the repetitive capability of processes to produce intrinsic dimensions of a feature within the specified tolerances.
- Machining time parameter
  It considers the machining time which is the amount of time taken for removing the feature volume by the machining process.
- Setup parameter
  It estimates the number of setups required to machine the part which is determined primarily by the approach direc-

tions of the features and the precedence constraints among them.

5 RELATING QUALITY PARAMETERS TO PLAN PARAMETERS

In order to support directed revision of process plans, we need to understand how the various quality metrics are connected to the operational features of a process plan. The left part of Figure 5 shows the dependencies between the quality parameters and plan parameters. The sequence accuracy and the process feasibility are not considered in the figure since they are the hard constraints which have to be satisfied by the process plans, and thus not negotiable. The sequence consistency relies on the type of the reference feature used since the achievable tolerances for the feature sequence is calculated using the following constraint (Hirode, 1996):

ConstraintSet: $on\_Location\_of\_EMV$
Distance direction Ve surface R = $dimn\_value$ $\pm$ 0.5%
Distance direction Ve axis R = $dimn\_value$ $\pm$ 1.0%
End ConstraintSet

This constraint implies that the variation in the distance between the feature and its reference can be maintained to a tolerance band of about 0.5% or 1.0% of the nominal dimension value, where 1% is for "axis" type of reference and 0.5% is for "surface" type of reference. The sequence air time is the time when no cutting is done but the tool is being moved from one position to another, and therefore it is purely dependent on the distance between the features. Accuracy and consistency at the process level check whether the process can meet the form, finish or the tolerances requirement. It is obvious that both of them depend on the specific process and process parameters (i.e, the flatness of a planar entity). The machining time relates to the spindle speed, feed and machine-table feed rate which are all process parameters. Also since the machining time is the time taken for removing the feature volume it should relate to the size of the feature volume. In current planning system, the number of setups is estimated by calculating the tool approach directions of the processes under the precedence constraints among the processes. So it depends on the feature order that defines the alternative precedence and the specific processes which determine its tool approach directions.

5.1 Plan Property Modification vs. Search Space Navigation

According to the relationship between a plan property and its dependency as described in Figure 5, every time ASUPPA changes one or more plan properties, it needs to decide which level of search space it should go to. Since sequence level only involves features, and process level relates to the processes, mappings from plan property modification to the different levels of search space are shown in the right part of Figure 5. The arrow head points to the search space level to which the planning system maps for each plan property's modification.

As shown in Figure 5, ASUPPA attempts to map the plan modification at two levels: *process level* and *sequence level*. In the process level, the planner uses the same feature sequence, but replaces some of the existing machining operations with different ones. This corresponds to changing the mappings from composite cells to machining operations. At the sequence level, the planner uses a different feature sequence with the same feature set as current one but in a different order or a completely different feature set to generate a good plan. The former corresponds to changing the order of features in the current plan, and may or may not result in the reordering of machining operations. The latter one disregards all the mappings for features which are no longer present in the new feature sequence and adds those mappings/features which were not present in the previous feature sequence. This method can be considered as a splitting and merging of the composite cells in the feature sequence. This results in a different feature sequence without the "bad" feature in the previous one and includes the new required features and as many previous "good" features as possible.

Note that improving machining time or number of setups can be mapped to either the sequence level or the process level. ASUPPA tries to improve them in process level first, and if there is no improvement that can be done, the system goes to the sequence level. The reason why ASUPPA chooses process level first is that changing a process rather than the feature sequence can minimize the ripple effects to other good plan properties, and thus make the new generated plan more predictable.

6 DEFAULT PLAN GENERATION (INNER LOOP)

In our process planning system, generating a default process plan is based on process level penalty cost and sequence level penalty cost. The lower the total process level and sequence level penalty costs of a process plan, the better the quality of the plan.

For each evaluation criteria, the penalty cost of a violation is one unit. The total cost for each level evaluation is the weighted sum of the violation cost for each criteria at that level:

$$C = \sum_{i=1}^{n} w_i * c_i$$

where c_i, w_i are the violation cost and the weight associated with each evaluation criteria. c_i is 1 if the current plan does not satisfy the corresponding evaluation criteria and 0 otherwise. n is the number of quality parameters at each level.

The following principles are considered when generating a default process plan.

- The default plan should satisfy the default evaluation criteria to the maximum degree.

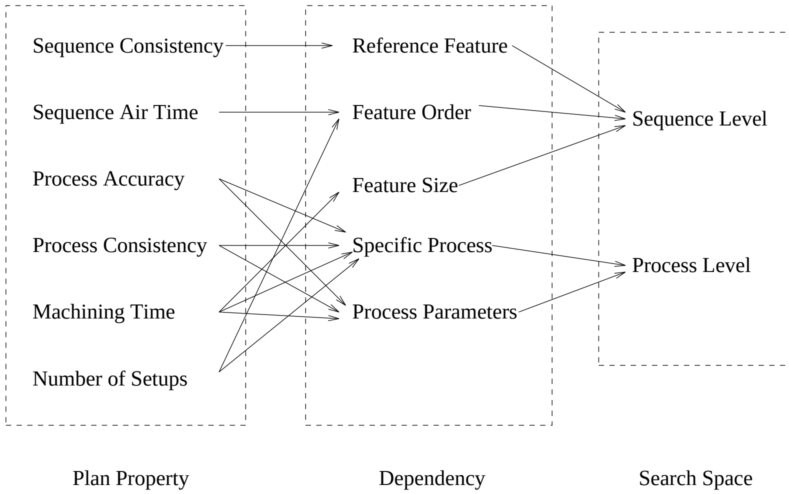

Figure 5. Plan Property Modification vs. Search Space Navigation

- The default plan should provide the user as much detailed information as possible, such as the result of each quality parameter applied to the plan, basic parameters such as machining time, air time, tool approach direction and tolerance information of the plan. This will help the user give more accurate criticism of the plan.
- The default process plan should satisfy the basic manufacturing characteristics.

The default process plan generation considers two basic manufacturing characteristics. The first is whether the referenced feature is machined first (the function of accuracy parameter in sequence level evaluation). The second is whether a process has size capability to machine a feature (the function of feasibility parameter in process level evaluation). Incorporating these two properties of a plan helps the planning system narrow the search space of feature sequences and corresponding process plans.

The detailed steps to generate a default process plan are:

- Step 1: Evaluate all feature sequences F_1,F_2,...,F_m;
- Step 2: Pick F_i,F_j,...,F_k which have the same minimal sequence level cost C_{seq};
- Step 3: Generate process plans for arbitrary one feature sequence, say F_g, $i \leq g \leq k$;
- Step 4: Evaluate process plans P_{g1}, P_{g2}, ..., P_{gk}, and group those which have the minimal process level cost C_{pro} and whose machining time or number of setups does not meet the system's built-in requirement, but the deviation value is the minimal into a set P. Taking into account that the setup cost is more expensive than the machining cost, we always choose the plan whose number of setups is minimal. For the plans whose process level cost, number of setups and machining time are the same, but the process names are different, the planning system treats them as equivalent. Therefore, there is only one such plan, P_{gi}. According to Figure 5, the system can only change the current plan's machining time or the number of setups. This is done by trying to find a new feature sequence to expand. There are two reasons for this. First, the corresponding feature sequence of the current plan already has a minimal sequence cost which indicates nothing can be done in current feature sequence. Secondly, the process accuracy and consistency only relate to a specific process and its parameters, but the current plan's process level cost is already minimal with respect to its feature sequence. If no further improvement can be done, we skip to Step 6.
- Step 5: Find a new feature sequence F_l using the strategies described in Section 8.3. Because the goal of the planning system is to generate a process plan whose total cost is minimal, it is reasonable to restrict the focus of the feature sequences generated by improving the machining time or the number of setups to the feature sequences with minimal C_{seq}, that's F_i, F_j, .., F_k. Then we go to Step 3 with F_l, where $i \leq l \leq k$, and $l \neq g$.
- Step 6: Choose a process plan with minimal total cost from existing plans, and present it to the user.

It is seen that when generating a default process plan, all feature sequences are evaluated using the sequence level quality parameters. The planning system remembers each evaluation criteria cost and operation time associated with every feature sequence to use in improving the process plan. Although the default process plan's corresponding feature sequence has minimal sequence level penalty cost, and default process plan has minimal process level penalty cost with respect to this feature sequence, it may not be the plan with minimal total cost of sequence level and process level penalty costs.

7 STRUCTURING THE INTERACTION WITH THE EXPERT

Three factors are considered when choosing the allowable user criticisms. First since ASUPPA acts as a process planner's assistant, it should depend on the user occasionally but not completely, otherwise, it will force the user to do all the planning. Second, since different users have different preferences on the plan, the interface should allow the user to specify their preferences. Third, the planning system should provide a mechanism to allow the user to change the plan objectives. Therefore, the planning system supports the user to critique current process plan in terms of evaluation metrics for certain aspects. For other aspects, more specific preferences or limitations are used to reflect new plan objectives. Based on each type of criticism and the relations between the properties of a plan and plan improvement discussed in Section 5, the system modifies a plan by dealing with the interactions among the criticisms and navigating the search space of the process plan.

The planning system assumes that the user is satisfied with the properties of a plan which the user does not criticize. So when ASUPPA improves the plan, it will try to keep these properties the same as before. For example, if the user asks the planning system to improve the machining time of a particular feature, the planning system will try to replace the current process first to reduce the machining time. If this fails, the system will generate a new feature set which does not include the criticized feature and is maximally similar to the original one, assuming that the user is satisfied by the machining time of other features in the sequence set. Two feature sets are maximally similar when they have maximum number of same features.

The planning system provides the user nine ways to criticize the current process plan. Six of these are based on the quality parameters. One is used to criticize the plan by changing the weights. Others require the user's input to directly change the plan or the manufacturing environment.

Six criticisms based on the plan evaluation criteria are :

- Feature sequence consistency
- Feature sequence air time
- Process accuracy
- Process consistency
- Machining time
- Number of Setup

The above six criticisms are in the form of "Yes" or "No" to specify whether the user is satisfied with these properties associated with the current plan. The planner takes the user's criticisms, reasons with the interactions between them, and chooses the direction to improve the plan.

Three other criticisms are used independently because the user has to provide more detailed information about the current plan. This may sometimes even cause the planning system to start from scratch completely. These criticisms allow the user to:

- Specify a different order of feature sequence
- Modify the manufacturing environment by adding/removing processes
- Change the weights associated to each evaluation criteria

8 MAPPING USER CRITICISMS TO IMPROVE A PROCESS PLAN

From Figure 5, we can see that criticisms to sequence consistency and sequence air time will be mapped to the search space of sequence level. Criticisms to the process consistency and process accuracy will be mapped to the search space of process level. The criticisms to the machining time or the number of setups can be mapped to the search space of either the sequence level or the process level. It's obvious that when the user specifies a different feature sequence order, such criticism will be mapped to the sequence level search space. If the user removes a machining process, the criticism will be mapped to the process level search space. If the user changes the weight or adds new machining processes, the planning system must restart its operation from scratch. The following subsections will discuss in detail on how to map the criticisms based on quality parameters to different levels of search space.

8.1 Sequence Level Improvement

There are four criticisms based on quality parameters which are mapped to the search space of sequence level: sequence consistency, sequence air time, machining time and number of setups.

- Sequence consistency/Air time improvement
  Sequence consistency/air time improvement can be done by the planning system finding a sequence with both lower consistency cost/air time and maximum similarity to the current feature sequence.
- Machining time improvement
  The machining time is proportional to the amount of material being removed and has nothing to do with the feature or operation orderings. Therefore, the machining time improvement in the sequence level is implemented by applying the Split_Merge method (Li, 1997) to split the feature with the maximum machining time (called "bad" feature). A new feature sequence is generated, which not only includes the part of the "bad" feature but also is maximum similar to the current one.
- Number of Setups
  In the inner loop, the improvement of the number of setups in the sequence level is carried by searching a feature sequence which has the same feature set as the current one, but in a different order. This is obtained by reasoning about current process plan setup so that the tool approach directions of the corresponding process plans can be reduced. In the outer

loop, the improvement of number of setups in the sequence level is implemented by finding the feature sequences maximum similarly whose other properties are not worse than those of the current feature sequence.

8.2 Process Level Improvement

According to Figure 5, the criticisms to the process level quality parameters are all mapped to the search space of the process level.

- Process Consistency/Accuracy Improvement
  The planning system picks up the process with maximum consistency/accuracy cost in the current plan. It searches greedily the process set that it belongs to, which is generated when the corresponding feature is input to the process selector module, and replaces by a set with lower consistency/accuracy cost.
- Machining time improvement
  At the process level, the machining time improvement is done by replacing the process which has the biggest machining time by another one with lower machining time.
- Setup Number Improvement
  The planning system first determines which process causes the increase in the number of setup by reasoning about its tool approach direction. Then it replaces it with one chosen from the process set that has a tool approach direction which can reduce the number of setup of the current process plan.

Each process plan improvement is actually an iterative procedure in the sense that if the planning system can not find a better process, or the chosen feature is an atomic cell which can not be split, it goes back to the appropriate level (process or sequence level). It chooses the current worst process or feature existing in the original process plan or feature sequence excluding the processes or features already considered.

We should also note that at each level, the planning system always uses a greedy algorithm to find the better process or feature sequence. The reason we can do this without reducing the speed of generating a good process plan is because the space at each level is small while their combination is very large.

8.3 Handling Interactions Between Criticisms

The planning system provides the user an interface for the six kinds of criticisms based on evaluation criteria. It has the ability to handle the interactions among these criticisms, and make tradeoffs to generate a process plan with overall good quality.

In the process planning system, the criticism factors influence one another. The influence of a partial change may propagate. There is no guarantee that a globally optimal solution is always obtained. However our planning system provides four kinds of strategies to decouple the interactions among the criticisms to help the generation of a satisfied solution.

- Conservative
  This strategy improves the unacceptable property that has the biggest weight.
- Aggressive
  This strategy improves the unacceptable property whose change affects the maximum number of other properties.
- Greedy
  This strategy improves all unacceptable properties independently at the same time.
- Random
  This strategy chooses a non-visited feature sequence whose cost is the least in the existing non-visited sequences.

ASUPPA's basic strategy is aggressive. Only when an unproductive situation is detected, the planning system tries the other three strategies in the decreasing priority, as explained below.

Unproductive situation occurs when the planner keeps producing equivalent or worse plans. An equivalent plan is a plan visited before, or a non-visited plan whose properties are the same as those of a visited plan. A worse plan may have some properties improved, but the overall quality is lower. Unproductive situation can be detected by checking the visit flag of a plan, comparing the plan properties, and plan penalty cost.

The aggressive strategy used by the planner to improve the plan considers the following factors in a decreasing order of importance:

- The dependency list of the plan properties to be improved.
- The number of properties affected by the improvement of each criteria.
- The possibilities of not affecting the criteria that are already good.
- The weight of each criteria.
- The running time to get a new process plan.

There are 67 combinations of possible different criticisms given by the user. The combination of 6 criticisms based on evaluation metric is 64 plus 3 more independently used criticisms. Before the planner begins to improve the plan, it will recall the cost associated with the sequence consistency and the process consistency, the sequence air time, the current plan machining time and the current plan setup number. These are used as the references to generate better process plan.

8.4 Learning User's Expectation on the Plan

To help convergence in generating a good process plan and detect any conflicts in the user's criticisms, the planning system is equipped with a simple learning mechanism. The mechanism allows the planning system to adjust its plan quality range by reasoning with the user's criticisms to the current process plan. The more the planning system knows about the user's expectations, the easier it is for the planning system to determine the direction in which to improve.

More specifically, the learning procedure involves the following steps:

- Recall the current plan's score.
- Each time the user gives the criticism of the plan, the planning system checks whether the user's criticism contradicts his previous actions. If so, the planning system displays the conflicts to the user, and asks him to revise his criticism. Otherwise, the planning system updates the properties' acceptable range for the next loop of plan improvement.

Please note that there exists difference between the inconsistent user criticism and user changing the evaluation criteria. The inconsistent user criticism means there is at least a conflict in the user's critiquing actions, and is caused by the user changing the evaluation criteria several times and may forget what his previous actions were. ASUPPA handles the inconsistent user criticism by presenting the conflicts to the user and requiring the user to revise his criticism. ASUPPA handles the user changing criteria by first detecting the inconsistent user criticism, updating the properties' acceptable range for the next loop of plan improvement, determining the improvement direction, and finding a plan which satisfies the user.

9 EXAMPLE

A case study part and its volume decomposition is shown in Figure 6. The case study is designed to test the major capabilities of the planning system by comparing the time and the process plan search space visited to find the same plan to the exhaustive approach. In designing an evaluation, we typically measure whether the developed planning system can find the required plan through the criticisms and how fast it is.

Figure 7 is the first feature sequence chosen by ASUPPA to expand for generating the default process plan according to the procedure defined in Section 6. The generated process plan details are illustrated in Figure 8. Since the number of setups and machining time did not satisfy the predefined criteria, the planning system improved it itself before presenting the plan to the user. Its improvement is shown in Figure 9 and Figure 10. It is seen that the plan machining time and sequence air time have been improved. But the number of setups remains the same because the planning system could not improve it in the inner loop. In this example, the planning system expands three feature sequences when generating the default process plan.

Figures 11 and 12 show the best process plan found by using the exhaustive search technique. After ASUPPA generates the default process plan and presents it to the user, when the user types "No" for the plan machining time and number of setups, the planning system iterates and finally comes up with the same plan in a short time and visiting less of the search space (see Table 1). The unit to measure the plan search space is the number of the feature sequence expanded. The time for our approach in Table 1 excludes that for the user criticisms. It is seen that in this case ASUPPA is able to find the process plan which not only satisfies the user but also in less time than an exhaustive search.

10 DISCUSSION AND CONCLUSION

In this paper, we presented a plan refinement framework called ASUPPA that can act as a "process planner's assistant" to human process planners. We argued that automation of process planning is best done through interactive process planning assistants that can handle changing quality criteria. Stand-alone process planning systems with pre-specified objective functions can not do that. We concentrate on how a plan is evaluated, what is the relationship between plan properties and plan modification, and how a default plan is generated. We also show what the allowable user criticisms are, how the user's criticisms can be used to navigate the process plan search space, how the interactions among different criticisms are handled so that a plan can be modified to be acceptable. The planning system is equipped with a simple learning mechanism to help solution convergence. Conceptually, ASUPPA can be seen as navigating the search space that is set up by ASUFTB, aided by its evaluation module, user criticisms and learning capability. This type of process planning approach can provide the right balance between completely automated and user-assisted process planning.

ASUPPA system builds on, and is thus related to, several previous process planning systems. The iterative operation of ASUPPA is closely related to the "iterative redesign" used in the DOMINIC system (Dixon, 1986). The differences stem mainly from the rich structure of process plans in ASUFTB/ASUPPA as compared to the parametric designs that are improved in DOMINIC. This makes the "modification" of plans considerably more involved in ASUPPA. The importance of plan refinement in process planning has been recognized in systems such as Nextcut (Kambhampati, 1993). A difference is that while systems such as Nextcut are best seen as assistants that offer process planning advice to designers, ASUPPA should be seen as an assistant to expert process planners. Another difference between ASUPPA and the Nextcut process planning system is that ASUPPA is based on a more systematic feature interpretation framework. ASUPPA is also closely related to the IMACS system (Gupta, 1994). The primary difference is that while IMACS is intended to be a standalone process planner, ASUPPA is designed to be a process planner's assistant. Accordingly, IMACS is driven by a multilevel branch and bound search that seeks to find a plan that is optimal with respect to a pre-specified optimality metric, while ASUPPA is driven by an iterative improvement search that aims to find a plan that satisfies the inner and outer (user) evaluation. Both systems are based on first principles substrates that support enumerating and handling multiple interpretations of the given part.

Used Approach	Time (seconds)	Visited Plan Search Space
Exhaustive	3983	85
Interactive and Iterative	911	16

Table 1. Performance Comparison between Exhaustive Approach and Iterative and Interactive Approach for Example in Figure 6

We will continue to evaluate our planning system by running more cases, and also improve production cost and time models to reflect real manufacturing environments.

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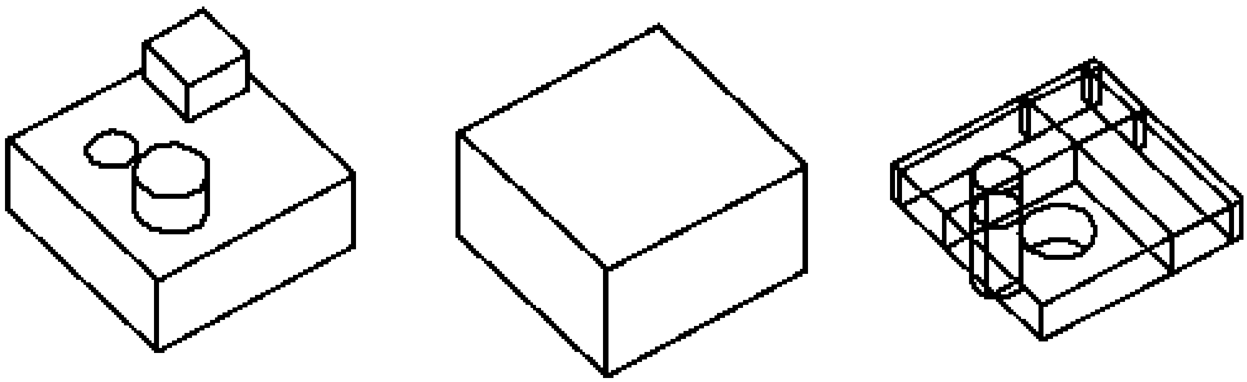


Part Stock Removal Volume

Figure 6. Example

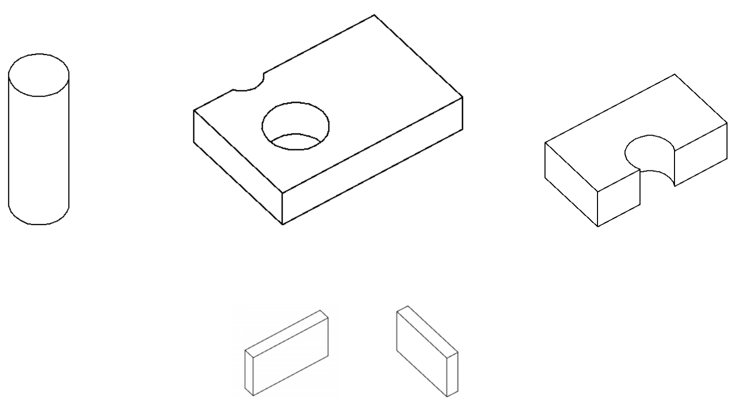
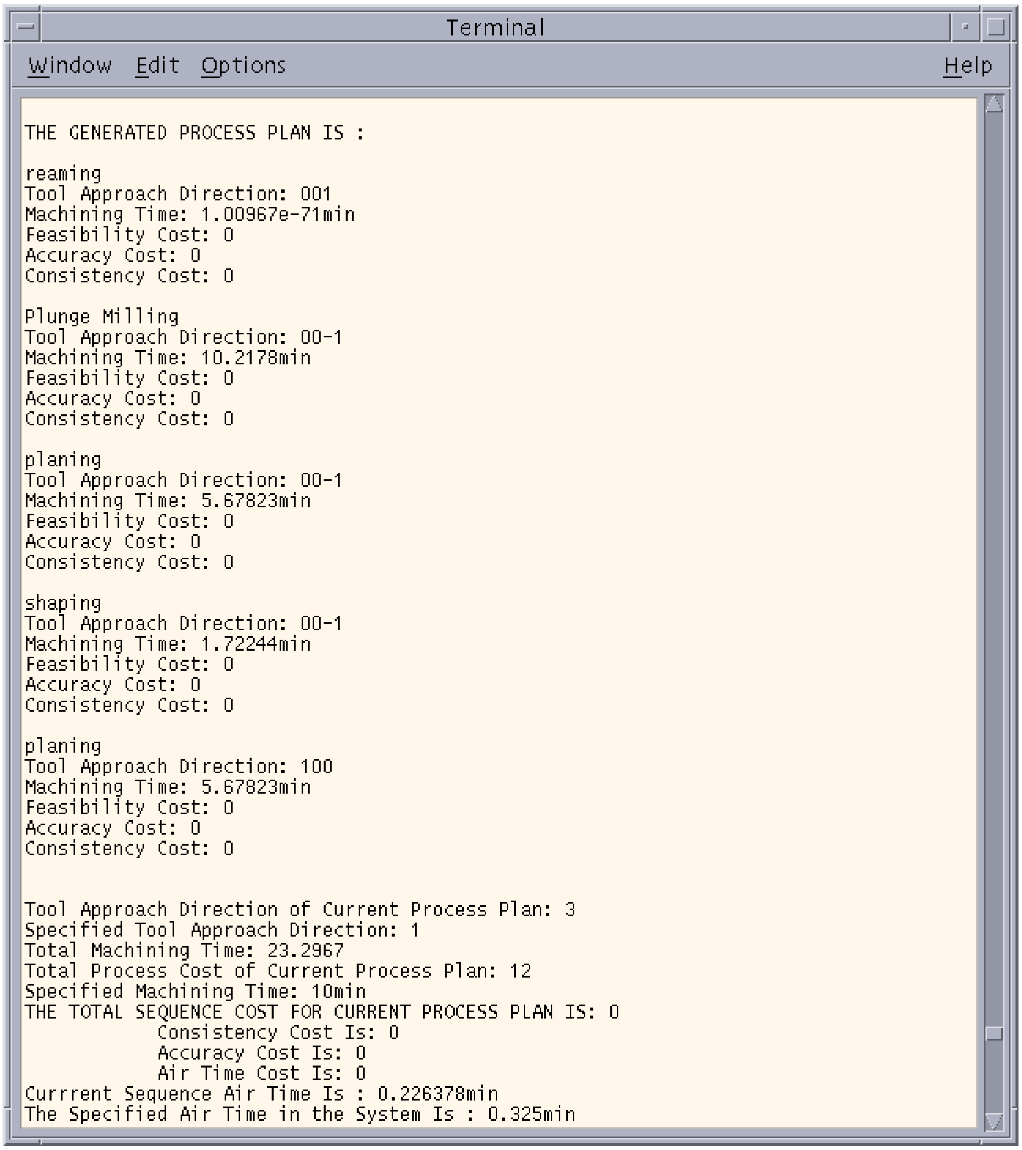


Figure 7. First Feature Sequence Choosn by ASUPPA to Expand



```
THE GENERATED PROCESS PLAN IS :

reaming
Tool Approach Direction: 001
Machining Time: 1.00967e-71min
Feasibility Cost: 0
Accuracy Cost: 0
Consistency Cost: 0

Plunge Milling
Tool Approach Direction: 00-1
Machining Time: 10.2178min
Feasibility Cost: 0
Accuracy Cost: 0
Consistency Cost: 0

planing
Tool Approach Direction: 00-1
Machining Time: 5.67823min
Feasibility Cost: 0
Accuracy Cost: 0
Consistency Cost: 0

shaping
Tool Approach Direction: 00-1
Machining Time: 1.72244min
Feasibility Cost: 0
Accuracy Cost: 0
Consistency Cost: 0

planing
Tool Approach Direction: 100
Machining Time: 5.67823min
Feasibility Cost: 0
Accuracy Cost: 0
Consistency Cost: 0


Tool Approach Direction of Current Process Plan: 3
Specified Tool Approach Direction: 1
Total Machining Time: 23.2967
Total Process Cost of Current Process Plan: 12
Specified Machining Time: 10min
THE TOTAL SEQUENCE COST FOR CURRENT PROCESS PLAN IS: 0
            Consistency Cost Is: 0
            Accuracy Cost Is: 0
            Air Time Cost Is: 0
Currrent Sequence Air Time Is : 0.226378min
The Specified Air Time in the System Is : 0.325min
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Figure 8. Process Plan for Sequence in Figure 7

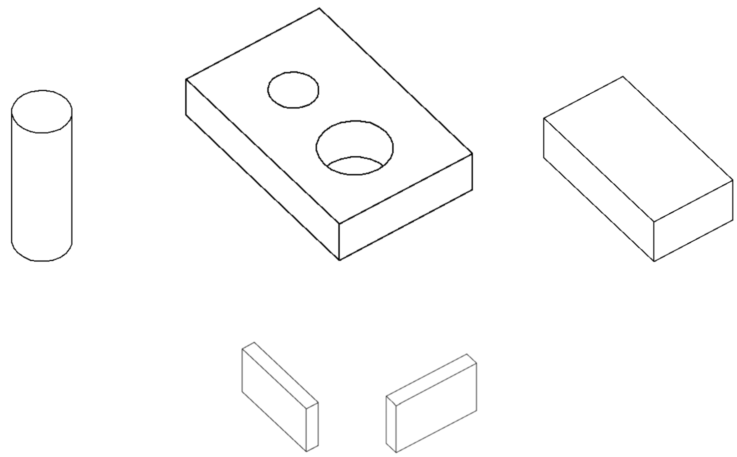

Figure 9. Improved Feature Sequence

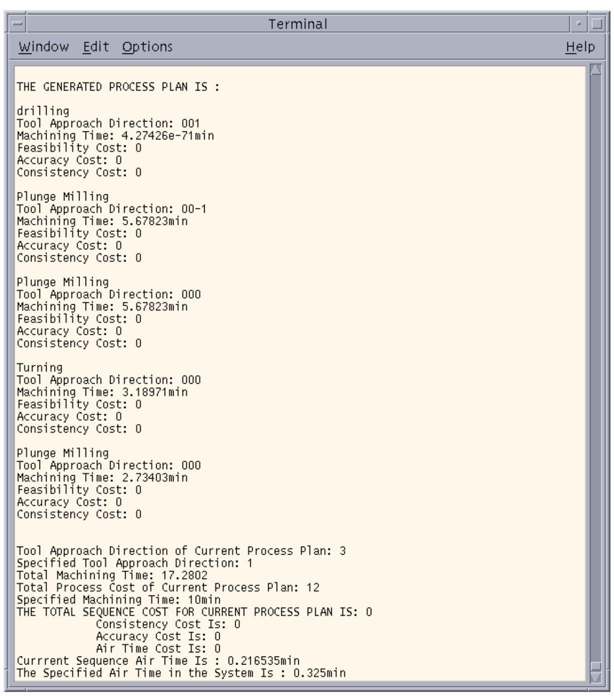

Figure 10. Process Plan for Sequence in Figure 9

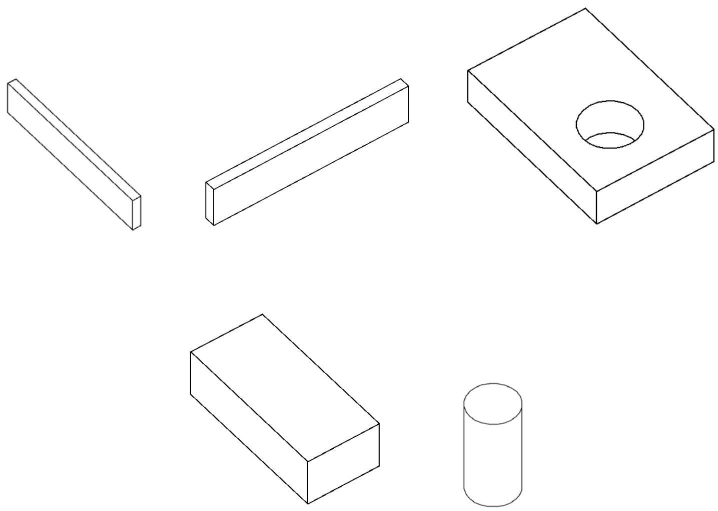

Figure 11. Process Plan Satisfying the User–Feature Sequence

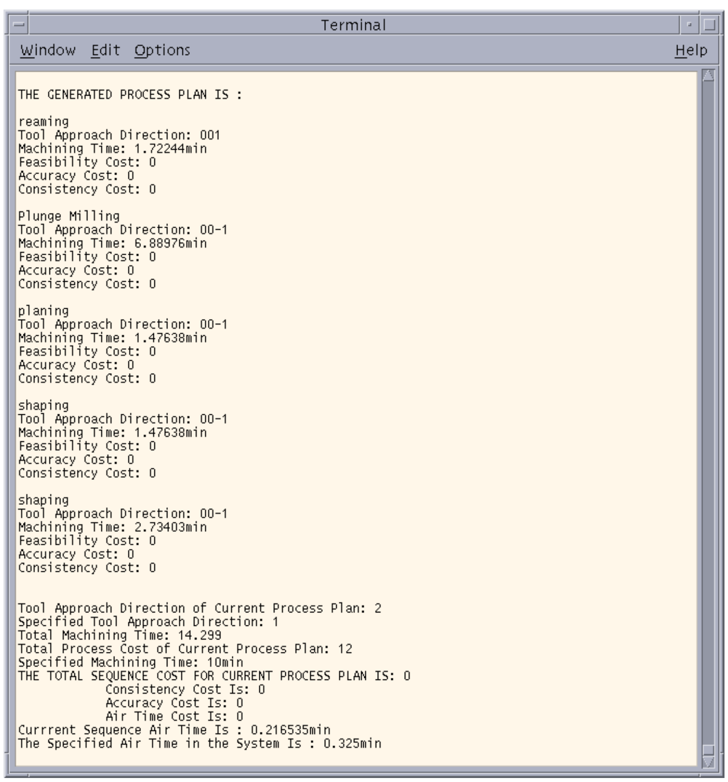

Figure 12. Process Plan Satifying the User–Plan Details