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by

M. E. Ssemakula, D.S. Nau,
R. M. Rangachar and Q. Yang

SYSTEMS RESEARCH CENTER

UNIVERSITY OF MARYLAND

COLLEGE PARK, MARYLAND 20742

Optimal Process Sequencing in CAPP Systems

Mukasa E. Ssemakula*
Dana S. Nau†
Ramesh M. Rangachar‡
Qiang Yang§

University of Maryland, College Park, MD 20742, USA.

Abstract

Automated Process Planning forms an important link in CIM Systems. Process Sequencing is one of the most important phases of process planning and is influenced by factors such as part geometry, available manufacturing resources and generated cutting forces. This paper describes a new AI based approach to optimizing this function using heuristic search techniques.

1 Introduction

Process planning is one of the basic tasks to be performed in manufacturing systems. It is a detailed and difficult task traditionally carried out by highly skilled workers who have an intimate knowledge of a wide range of manufacturing processes and are themselves experienced machine operators. Many of the people with these skills are now past middle age and fast approaching retirement while there are few adequate replacements among the younger generation. In addition, there is generally a lack of consistency among process plans prepared by different individuals with varying manufacturing backgrounds and levels of skill.

For reasons such as these, there has been increasing interest in ways to automate the process planning function. By using a computer, the tedious and repetitive aspects of process planning can be speeded up and this helps to optimize the total manufacturing function by releasing the experienced planners and enabling them to concentrate on those aspects outside the scope of a computer [11]. At the same time, more consistent process plans can be obtained by applying a standard set of rules which increases confidence in the system and helps in the rationalization of production. To automate process planning, the logic, judgement, and experience required for process planning must be captured and incorporated into a computer program.

AI techniques can aid in automating several of the reasoning activities required for process planning. To date, several different systems have been developed that use AI techniques for Process Planning. This paper discusses how AI techniques can be used in the optimization of process sequences. Based on the nature of the problems involved in process sequencing, we analyze the

*Mechanical Engineering Department and Systems Research Center
†Computer Science Department, Systems Research Center and Institute for Advanced Computer Studies
‡Mechanical Engineering Department
§Computer Science Department

computational complexity of process sequence optimization, and describe some algorithms for optimization of process sequences based on heuristic search techniques.

2 Background

Briefly defined, process planning is that function which determines the sequence of individual manufacturing operations needed to produce a given part or product as well as associated machining conditions (feed, speed, etc.). In effect it is the subsystem responsible for the conversion of design data into work instructions [17]. The resulting operation sequence is documented on a form, along with the required machine tools, cutting tools and operation times. Such a form is known as a process plan. When a new part is to be produced at the shop, the manufacturing engineer prepares a process plan. The process plan is dependent on the experience and judgement of the planner. It is his responsibility to determine optimum process plans. Following are the different phases of process planning [17].

1. Selection of operations.
2. Sequencing the operations.
3. Selection of the machine tools.
4. Selection of the workpiece holding devices and datum surfaces.
5. Selection of cutting tools.
6. Determination of proper cutting conditions.
7. Determination of cutting times and non-machining times.
8. Editing the process sheet.

2.1 Types of CAPP Systems

2.1.1 Variant Process Planning:

Variant process planning techniques use part classification and coding along with the concepts of Group Technology. The parts are classified according to their geometric similarities and manufacturing characteristics. Standard plans for each part family are stored in a part family matrix. To obtain a process plan for a new component, the code for the part is determined and the plan is retrieved if a similar part is found in the part family matrix. The user can examine and edit the plan. The new plan can be put into the part family matrix for future reference. Some examples of variant process planning systems are MIPLAN [6], CAPP [15], and TOJICAPP [19].

The main criticism to be made of variant process planning systems is that they do not fundamentally solve the problem. They rely on expert process planners to develop standard process plans and therefore lock in many of the difficulties and problems associated with manual systems [14]. Variant systems do not generate *new* process plans. It is for this reason that generative process planning was developed. Variant systems are still dominant in industry however, because they are easy to implement, they can handle a wide variety of parts and conceptually, they are very similar to what has been in the past and therefore are easily accepted.

2.1.2 Generative Process Planning:

In a generative system, an individual plan is created from scratch for each part. Based on an analysis of the part geometry, material and other factors which would influence manufacturing decisions, the system generates a *new* process plan for each part. The manufacturing logic, formulae to determine machining conditions and standard times will be used by the system to produce the process plan. Some examples of generative systems are AUTAP [16], ICAPP [12], [13], and TIPPS [1].

2.2 Required Advances in CAPP

It is the generative process planning system that can link CAD and CAM together, but the lack of a good interface with a CAD system is the greatest handicap the researchers are facing. Thus, most of the researchers, many from Computer Science are working in this area to develop automatic feature recognition systems. Meanwhile, the lack of a feature recognition system has slowed down the automation of the different phases of process planning described above. Though there are many systems that determine required operations, cutting parameters and production times, very few systems attempt to sequence the operations optimally or select jigs and fixtures. Another reason for this is the lack of universally accepted manufacturing logic for process sequencing and selection of jigs and fixtures. Most of the process planners use their experience for these phases of process planning. Nowadays, Artificial Intelligence (AI) systems are accomplishing useful practical results in science and technology. Expert systems, i.e., computer systems which use application-specific problem-solving knowledge to achieve a high level of performance in the field which we would think of as requiring a human expert, may be used to automate some phases of process planning. There are several expert process planning systems that have automated some phases of process planning that lead towards CIM. Some systems are SIPS [9], GARI [3], TOM [7], and EXCAP [2].

3 Process Sequencing

Process sequencing is the task of arranging the processes chosen to produce a part in a proper order or sequence, so as to obtain a reasonable process sequence (if possible, the optimum sequence) which can be used to manufacture the component. As already stated, there are very few accepted rules for process sequencing. Therefore, an industrial survey was conducted to study the process planning techniques being used in industry [10]. The survey revealed that process sequencing does not lend itself to a perfect methodology. Bootawallah conducted a similar study on a family of 425 spur gears and obtained 377 different process plans [5]. This is not surprising because process sequencing is strictly a human oriented activity, highly dependent on individual skills, human memory and mood, and a mass of reference manuals. Though it is human-oriented, there are certain factors that must be considered while selecting a particular process sequence. Some of the important factors that need to be considered were found to include part geometry, workpiece material, batch size, as well as available resources (e.g. machine tools, cutting tools, labor) and their capabilities.

The ultimate objective of process sequencing is to minimize the cost of production without sacrificing the quality of the product. The total production cost is given by [4]

$$C_{pc} = C_o(T_m + T_h) + T_m(C_t + C_oT_{tc})/T \tag{1}$$

where

C_{pc} = cost per work piece, \$/piece,
C_o = cost to operate the machine tool, \$/min,
T_m = machining time, min,
T_h = handling time, min,
C_t = cost of tooling, \$/cutting edge,
T= tool life, min,
T_{tc} = tool change time, min.

In the above equation, C_{pc} can be decreased by decreasing C_o, C_t, T_m, T_h and T_{tc}, or by increasing T. The value of C_o is dependent on the labor cost, the machine cost and the applicable overheads. Although the estimated value of C_o varies from one company to another, it will be constant within a particular firm. C_t, T, and T_{tc} are also constants in a given situation and should not affect the optimization problem. Thus T_m and T_h are the most important process sequencing variables to consider in trying to optimize the production cost C_{pc}. The values of T_m and T_h are fairly similar for a given combination of machine tools, cutting tools and workpiece material across industries. Therefore, for a general application program, it is possible to minimize C_{pc} by minimizing T_m and T_h. Thus, the objective is to minimize T_m and T_h to minimize the production cost. Of these, T_h is the one most significantly affected by the sequence of operations.

4 Process Sequence Optimization

When the total time a component spends on a machine is analyzed, it can be seen that the total handling time is about 70% of the total time and the total machining time is 30% [8]. Since handling time is usually more than machining time, reduction of handling time is generally more important than reduction of machining time. Handling time consists of work handling time and tool handling time; each is briefly discussed below.

In this discussion, we assume that the workpiece is described as a collection of *machinable features*, each of which either already exists in the original piece of stock, or else must be created by a sequence of one or more machining operations. We assume that for each feature F, we have already determined the following information:

1. The identity of the surface in which F is to be machined.

2. One or more possible sequences of machining operations to use in creating F.

3. For each machining operation, the machines, cutting tools, and the tool trajectory (or trajectories, if more than one is possible) which must be used for that operation.

Some of this information may be changed by the process sequence optimization procedure.

4.1 Work Handling Time

Reduction of work handling time means that the number of times the component is reset on the machine must be reduced. Therefore, all possible operations that can be performed during a particular setup must be completed before resetting the work piece. Fortunately, this is in accordance with a manufacturing rule of thumb which says 'try to finish as many operations as possible in one set up so that dimensional tolerances can be maintained.' Thus, the goal here is to minimize the number of setups. This can be done by grouping together the operations to be performed on the *same face using the same machine*. Once the operations are arranged as such, the work handling time will be minimum. This is based on the assumption that each feature on which machining operations are to be carried out is associated with a particular face.

4.2 Tool Handling Time

Different operations to be performed within a setup may require using different tools, which involves tool handling time. Tool handling time is the time required for all the tool changes that take place during the use of a particular machine. The number of tool changes can be reduced by the use of three strategies:

1. Group together (as much as possible) all operations requiring the same tool. For example, if two holes of the same diameter are to be created using spade drilling, then doing the two spade drilling operations at the same time will avoid a tool change.

2. If the tool diameter for an operation is not critical, change the tool diameter to allow the operation to be grouped together with other operations. For example, if there are different operations requiring center drills of diameters 3.5 mm, 4 mm and 5 mm, then all three center-drilling operations can be performed using the same center drill. The tools can be changed for other operations also, but one must be careful while doing this. For example, if the finished hole diameter is 25 mm, it must not be changed to 24 mm or 26 mm. Also, if threading and reaming should be performed, the intermediate diameters must be selected carefully.

3. Choose a different process plan for making a particular feature, if this will allow the processes in the plan to be grouped together with other operations for other features in a better way. For example, if two holes h_1 and h_2 of the same diameter are to be created using twist drilling and spade drilling, respectively, then a tool change can be avoided by creating h_1 using spade drilling instead of twist drilling. When such changes are made in the process plan for a feature, it is important to ensure that the new plan will still satisfy the required surface finish and machining tolerances.

Depending on the number of plans available for each machining feature, we have different ways for minimizing the number of tool changes. Below, we discuss the case of one plan for each feature and the case of more than one plan for each feature seperately.

4.3 One Plan for Each Feature

When there is one plan available for each feature, we can simply group all the operations requiring the same tool together, so that the number of tool changes can be minimized. This is possible because operations in the machining domain have a special property: there is a partial order over the set of operations required for a given feature; e.g., if O_1 is before O_2 in one plan, then O_2 cannot be before O_1 in any other plan for the same feature.

Inter-facial tool handling time is the time required to change tools when the setup of the part on the machine has been changed. The change of tool requires time. If the sequence of operations on each face is arranged such that the tool that was used for the last operation on face 'f' can be used for the first operation on face 'f+1', keeping the machine constant, then there will be some reduction in the tool handling time. This depends on the type of operation. For example, a twist drill cannot be used before using a center drill unless a pre-drilled hole is present. Threading cannot be done before drilling a hole. Therefore, the 'precedence relationships' of the different operations are very important. It is very unlikely that all last operations on a given face 'f' use the same tool as the first operation on the next face 'f+1'. But it is possible that some of the faces might be arranged so that the inter-facial tool handling time between two consecutive faces is zero. Thus, it is possible to obtain a combination of such faces which will be subsets of the complete sequence of operations. These combinations of faces can be appended to obtain the best possible sequence.

When there is one plan available for each feature, the results of inter-facial tool handling time minimization will be a set of partially ordered plans, one for each face. We can use P_i to represent the i^{th} such plan. The relationship between the P_is can be represented by a directed acyclic graph, where vertex n_i represents the i^{th} face, and there is an edge from vertex n_i to n_j if there is an operation which is both one of the last operation in P_i and also one of the first operation in P_j. We can use V for the set of vertices and E for the set of edges. Given $G = (V, E)$, algorithm 1 below will return the optimal sequence of faces which will minimize the inter-facial tool handling time.

Algorithm 1.

Let v be a vertex in G. Also let $indegree(v)$ be the number of edges pointing at v, $outdegree(v)$ be the number of edges pointing away from v and $e(v)$ be the set of edges either pointing into or away from v. Let S be a set, initially empty.

While $V \neq \emptyset$ **do** *(V is the remaining vertex set)*
  If there exists a vertex v such that $indegree(v) = 1$ and $outdegree(v) = 0$ **then**
    $S := S \bigcup \{e(v)\}$
  else
    select a vertex v such that $outdegree(v) = 0$
    $S := S \bigcup \{any - edge - inc(v)\}$;
  End $\{If\}$
  $V := V - v$
  $E := E - e(v)$;
End $\{While\}$

This algorithm will terminate in time in the order of $(|E| + |V|)$. The algorithm has been implemented in our sequence optimization system called SEQUENCE. The operation of SEQUENCE will be described in section 5.

4.4 More Than One Plan For Each Feature

Usually, we will have more than one way available to us for making a feature. Different choises of process plans will result in global plans of different tool handling times. For example, consider the hole-creation operations again. Several different kinds of hole-creation operations are available (twist-drilling, spade-drilling, gun-drilling, etc.), as well as several different kinds of hole-improvement operations (reaming, boring, grinding, etc.). Similar operations can be merged thus eliminating the task of changing the cutting tool.

For example, suppose hole h_1 can be made by the plan

P_1: spade-drill h_1, then bore h_1;

and hole h_2 can be made by either of the plans

P_2: twist-drill h_2, then bore h_2;
P_2': spade-drill h_2, then bore h_2;

with $\text{cost}(P_2) < \text{cost}(P_2')$. If h_1 and h_2 have different diameters, then the least costly global plan will be to combine P_1 and P_2. This plan will require four tool changes. However, if they have the same diameter, then a less costly global plan can be found by combining P_1 and P_2', merging the two spade-drilling operations, and merging the two boring operations, and yielding the following global plan:

puton-spade-drill, spade-drill h_1, spade-drill h_2, puton-bore, bore h_1, bore h_2.

This process plan only requires two tool changes.

As in the last section, we will again distinquish between the optimization of inter and intra-facial tool handling cases.

4.4.1 Minimization of intra-facial tool handling time

In the case when there is more than one plan available, our optimization system has to choose one plan for each feature, such that after merging the operations of the same type, the global plan will have the minimum number of tool changes. It has been shown that such a problem is NP-hard[18]. However, we have found a good heuristic algorithm which will return the optimal set of plans.

Our heuristic algorithm is a version of best-first branch-and-bound search algorithm, which searches through a state space. The state space is a tree in which each state is a set of plans, one plan for each of the first k goals for some k. The initial state is the empty set (i.e., $k = 0$). If S is a state containing plans for the goals $G_1, G_2, \ldots, G_k$, then the immediate successors of S are all of the sets $S \cup \{P\}$ such that P is a plan for G_{k+1}. A goal state is any state in which plans have been chosen for all of the goals.

We define the cost of a state S to be the cost of the plan obtained by combining the plans in S and then merging; i.e.,

$$\text{cost}(S) = \text{cost}(\text{merge}(S)).$$

Clearly, $\text{cost}(S)$ is a lower bound on the cost of any successor of S, but a better lower bound can be found as follows. Suppose S contains plans for $G_1, \ldots, G_k$. For each $t > k$, let $P^*(S,t)$ be the plan P for G_t which minimizes $\text{cost}(\text{merge}(S \cup \{P\}))$. Let

$$L(S) = \max_{t>k} \text{cost}(\text{merge}(S \cup \{P^*(S,t)\})).$$

Then $L(S)$ is a lower bound on the cost of any successor to S. We have developed a way to compute this cost efficiently [18].

In the search algorithm, pruning is done by computing an upper bound on the cost of the best global plan. For each G_i, let $\text{best}(G_i)$ be the plan for G_i of least cost. The upper bound is

$$U = \text{cost}(\text{merge}\{\text{best}(G_1), \text{best}(G_2), \ldots, \text{best}(G_n)\}))$$

During the search, any state whose cost is greater than U can be discarded.

The search algorithm appears below. This algorithm is a best-first branch-and-bound search, and is guaranteed to return the optimal solution. Except for the use of U for pruning, this algorithm can also be thought of as a version of the A* search procedure, with $h(S) = L(S) - \text{cost}(S)$ as the heuristic function.

Algorithm 2.

```
A := (∅)          (A is the branch-and-bound active list)
U := upper bound, computed as described above
loop
    S := pop(A)          (remove the first element of the list)
    if S is a goal state then return S
    if L(S) ≤ U then begin
      B := the successors of S, in order of least L-value first
      put the members of B into A, and sort A
    end
repeat
```

In the worst case, Algorithm 2 takes exponential time. Since the global plan optimization problem is NP-hard, this is not surprising. What would be more interesting is how well Algorithm 2 does on the average. However, the structure of the global plan optimization problem is complicated enough that it is not clear how to characterize what an "average case" should be; and there is evidence that the "average case" will be different for each application area. Therefore, we have restricted ourselves to doing empirical studies of Algorithm 2's performance on a class of problems that seemed to us to be "reasonable." For the plans that we examined, Algorithm 2 examined only about 3% of the search space—but given the nature of our test, this should be considered solely as a preliminary result.

4.4.2 Minimization of inter-facial tool handling time

When we consider the optimization of tool handling time with features on different faces, one way to obtain a "good" solution is to first apply the algorithm 2 of the last section, then use algorithm 1 to get an ordering of the faces.

However, one may not be able to find the best solution in this way. An optimal solution will not only specify which plans are chosen for the features, but also specify an ordering of the faces so that the correct order of set up operations can be performed. In order to find the optimal answer, we may need to search through a much larger search space, which process may consume much more computational effort than necessary. On the other hand, the method we presented above can be thought of as a good approximation algorithm, whose solution will not be too far from the optimal answers. We are currently working on an implementation of this approach for a CAPP system capable of generating multiple plans for each component.

4.5 Minimization of machining time.(T_m)

After handling time has been minimized, the machining time reduction is considered. It should be noted that this is possible only if there are inter-dependent operations. Consider the part shown in Figure 1. The pocket P1 and the hole HT are on the same face. If the pocket is machined first, the machining time required to produce the hole can be reduced. This is an example of interacting or dependent features.

4.6 Selection of the final sequence.

Before selecting the best sequence, the database will have a number of possible sequences. The best sequence is selected by considering the weighting factor for each operation. It is good practice in manufacturing for operations having a greater weighting factor to be finished first so that much of the heat is carried away by the chips and less material is left for further machining. The final sequence considers this and selects the best sequence. The final sequence given by SEQUENCE is the best sequence obtainable with the present depth of knowledge the system possesses.

5 Example

The ideas discussed above have been implemented in our sequence optimization system called SEQUENCE. The current implementation is for the case of one plan per feature although that of multiple plans is also being studied. SEQUENCE is currently integrated with the ICAPP process planning system. It should be noted however that SEQUENCE is an independent module capable of accepting input from any CAPP system and operate on it to generate the best operations sequence, provided the input is in the correct format. SEQUENCE is only concerned with the sequencing problem, taking as input descriptive information about each operation consisting of the following data:

1. An operation identification number.
2. The machiner tool code.
3. Code for face on which the operation is to be performed.
4. Drawing code to identify the particular feature.
5. Operation type
6. Tool type
7. Tool diameter
8. Weighting factor (this is the ratio of the volume of material removed to produce a feature to the total volume of material removed to make the whole component).

The following is a typical input to SEQUENCE and is for the demonstration part shown in figure 1:

opn-id	machine	face	optyp	drcd	tool	tldia	wtfct
10.0	20.0	1.0	1.0	F1	1.0	200.0	3.4
20.0	20.0	2.0	2.0	S2	2.0	32.0	22.5
30.0	20.0	2.0	2.0	S3	2.0	32.0	22.5
40.0	20.0	1.0	5.0	HO	4.0	5.0	30.2
50.0	20.0	1.0	5.0	HO	5.0	34.0	30.2
60.0	20.0	5.0	3.0	SL	2.0	32.0	6.7
70.0	20.0	1.0	4.0	P1	3.0	35.0	2.2
80.0	20.0	3.0	1.0	F3	1.0	125.0	2.5

90.0	20.0	4.0	1.0	F4	1.0	160.0	2.6
100.0	20.0	6.0	5.0	HT	4.0	3.5	7.4
110.0	20.0	6.0	5.0	HT	5.0	26.0	7.4

This input is grouped by SEQUENCE such that all operations on the same face requiring the same machine will be processed in one set up thus minimizing the work handling time. SEQUENCE then arranges the operations on a face in the decreasing order of the weighting factors for features. That is, it processes the features with the highest weighting factor, and hence the feature requiring the bulk of material removal first. SEQUENCE has the capability to change tools if necessary, to help minimize the tool handling time. SEQUENCE also considers the dependencies existing between any two faces of a component, arranging the faces in a descending order of weighting factors of the features. SEQUENCE also prints messages to help the planner to take some precautions during machining. Further, SEQUENCE determines those operations which could be changed so as to reduce handling time, thereby attempting to get a more refined process sequence. The final sequence so obtained is then returned to ICAPP for further processing. The final output of SEQUENCE which forms the input to ICAPP is shown below.

Final Sequence

opn-id	machine	face	optyp	drcd	tool	tldia	wtfct
10.0	20.0	8.0	1.0	F1	1.0	200.0	3.4
70.0	20.0	8.0	4.0	P1	3.0	35.0	2.2
40.0	20.0	8.0	5.0	HO	4.0	5.0	30.2
100.0	20.0	1.0	5.0	HT	4.0	5.0	7.4
110.0	20.0	1.0	5.0	HT	5.0	26.0	7.4
50.0	20.0	1.0	5.0	HO	5.0	34.0	30.2
90.0	20.0	4.0	1.0	F4	1.0	160.0	2.6
80.0	20.0	3.0	1.0	F3	1.0	125.0	2.5
60.0	20.0	5.0	3.0	SL	2.0	32.0	6.7
20.0	20.0	2.0	2.0	S2	2.0	32.0	22.5
30.0	20.0	2.0	2.0	S3	2.0	32.0	22.5

The total production time resulting from the final sequence of operations was 93 minutes which represents a 17% saving when compared to the production time of 112 minutes for the original sequence [10]. The level of savings to be expected will clearly vary with the complexity of the part concerned but increasing complexity will also lead to increased savings by using the techniques outlined above.

6 Conclusion

This paper outlined the importance of improved manufacturing technology. CAD and CAM were defined and it was demonstated that CAPP was important for the integration of CAD and CAM. A review of several process planning systems--Variant and Generative--showed that very few systems were optimizing process sequences. It was shown that the important factors influencing a particular sequence are the part geometry, the available machines and cutting tools as well as required cutting forces. A methodology for process sequencing and the expert system developed by the authors for process sequence optimization were described and the pertinent algorithms presented.

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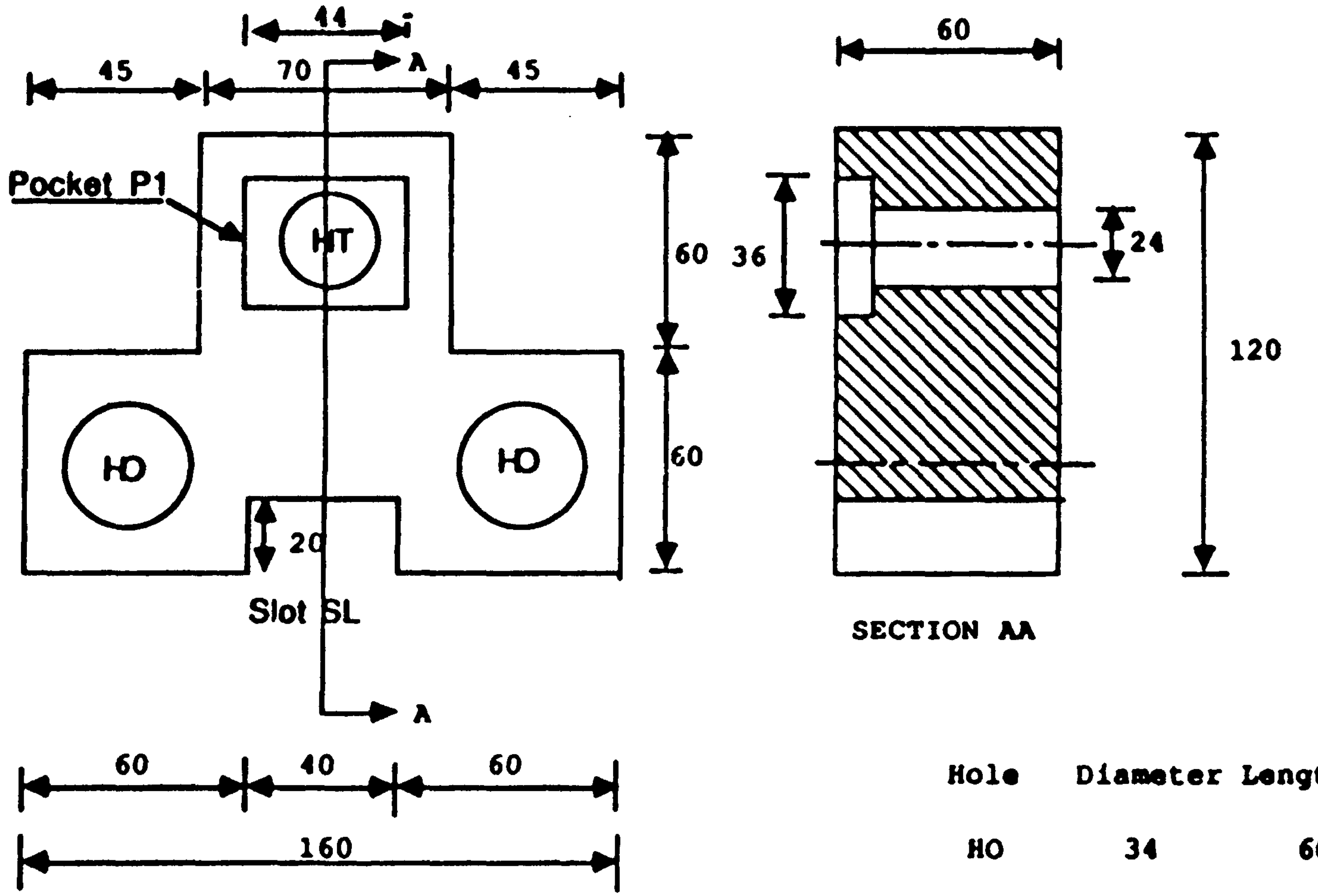

Hole	Diameter	Length
HO	34	60
HT	26	50

All dimensions are in mm

Figure 1: The Demonstration Part