Rule Based System for Non Linear Process Plan Generation

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Abstract: Considerable attention has been devoted in literature to potential advantages of non linear process plans, i.e. process plans that include parallel and alternative operations. Nevertheless up to now, in industrial practice all part programs have been strictly sequential and expert process planners are going on in developing linear process plans. In order to fill up the existing gap between potential benefits addressed in the literature and industrial practice, the paper proposes a new approach for translating linear strictly sequential process plans into non linear ones. In particular the paper focuses on the description of the AI module that contains all the technological knowledge required in order to relax precedence constraints. The approach, validated on a set of real part programs, has shown to be able to emulate expert process planners' ability in defining alternative process plans.

Keywords: Flexible Process Plan, Manufacturing System, Expert System

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1. Introduction

During the last decade, considerable attention has been devoted in literature to non linear process plans. Many authors [1-7] have pointed out the great opportunity that non linear process plans can offer in fulfilling the existing gap between planning and control. Real manufacturing systems are affected by a lot of disturbances like breakdowns, dynamic bottlenecks, unforeseen changes of jobs priority, etc. All these unexpected disruptions could be managed by replanning: requiring resources in a different order (changing the sequence in which operations are executed) or using alternative resources (for instance alternative tools). Unfortunately replanning is not an easy task and it cannot be quickly executed in real time. Thus different sequences and alternative operations have to be foreseen during the process planning phase, producing alternative process plans instead of traditional strictly sequential ones.

Although potential advantages of non linear process plans have been outlined and well-addressed in the literature, there is still a gap between academic research and manufacturing practice. To overcome this distance, a lot of efforts were made in the past in order to develop non linear Computer Aided Process Planning systems (CAPP). In particular two Esprit projects Flexplan [2] and Complan [7] dealt with non linear process plan generation. The reasons for the limited diffusion of these systems could be in principle related to the common difficulties CAPP systems have in generating feasible solutions for a wide range of part types and manufacturing operations.

To rapidly succeed in taking advantage of non linear process plan utilisation in real practice, the paper proposes a new approach that has the main objective of generating feasible alternative process plans. The new module, the Alternative Process Plan Generator (APPG), has been developed within the Brite project MOD FLEX PROD, which is devoted to the design and implementation of a new manufacturing system able to combine flexibility and productivity requirements. The idea underlying this new approach is to start translate existing strictly sequential part programs into non linear ones. The approach presents the main advantage of moving within feasibility: starting from an existing feasible solution (the sequential part program), it modifies it to obtain a non linear one, only by means of steps that do not affect feasibility of the process plan. Besides, the AI-based software module that represents the "clever core" of the APPG, contains a formalised synthesis of expert process planners' knowledge that could be easily utilised in other approaches. Indeed the set of rules implemented in this module, represents a robust framework on which other applications could be based on. While the general framework of the APPG is reported in [8], the paper focuses on the description of the submodule that contains the knowledge for non linear process plan generation.

The paper is organised as follows: Section 2 presents the general outline of the APPG approach, while the third one focuses on the sub-module that contains all the technological knowledge required for the precedence constraints elimination phase. In Section 4 results obtained by applying the APPG to a real case are reported. The results are compared with the non linear process plan generated by expert process planners, showing the feasibility and the capability of the approach. Finally the last Section of the paper presents the conclusions.

2. General Outline of the Approach

The objective of the APPG is to translate a linear part program into a non linear one, requiring only two types of information:

- ☐ *information on tools: a database on tools containing information on geometry and on the main characteristics (capabilities) of the tools used to machine the part;*
- ☐ *the original, strictly sequential, part program, describing the way in which tools are used (tool paths, cutting conditions) in order to obtain the finished part.*

Since the APPG takes as input the ISO part program of the part, the first submodule within APPG has the objective of translating information expressed in the ISO code in an opportune format. This submodule, the **Part Program Interpreter** (PPI), developed within the Brite project MOD FLEX PROD by CIMPA Aerospatiale (F), interprets the ISO instructions and translates them as a sequence of tool paths, that are basically characterised by the type of movement (linear, circular), the starting and the ending points of the path, the tool used and the cutting conditions adopted. The other fundamental information that the Part Program Interpreter reports as output, is the sequence in which each tool path appears in the initial part program.

In order to analyse the set of constraints that characterise the original part program and to decide which are the constraints that can be eliminated, the **Precedence Constraints Elimination** (PCE) module takes as input the output produced by the Part Program Interpreter. The module is basically composed of an Inference Engine, that contains the knowledge for deciding which are the constraints that can be eliminated without affecting the part requirements (essentially tolerances and roughness). Since this knowledge requires geometric analysis of relationship among tool paths, the Inference Engine is linked to a solid modeler module that acts as geometric calculator.

In order to derive alternative operations, a **Tooling Configurator and Selection module** (TCS) is also required. This module suggests alternative tools for substituting one or more tools used in the original part program. Indeed the Tooling Configurator is a module able to assess whether two or more tools can be substituted by a single multitask one (for instance a multidiameter boring bar), while the Tool Selection module suggests alternative tools for a given operation. This last module has the capability of suggesting alternative tools that can perform equally or better than the existing ones (in terms of roughness and tolerance). A sketch of the general architecture is reported in Figure 1, while a more detailed description of the APPG framework, the data structure adopted and the flow of information among sub-modules are reported in [8].

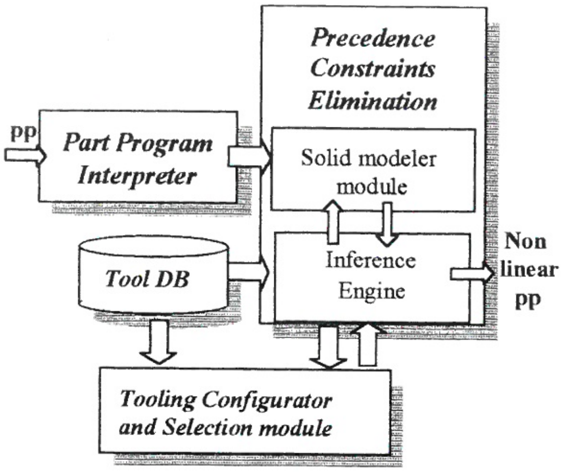

Figure 1. The Architecture of the APPG Module

The general framework described is wide in scope and implementation. In order to assess the viability of the proposed approach, the implementation phase has been managed step-wise. The attention has been thus concentrated, at first, on implementing a module that derives parallel operations (i.e. removes precedence constraints) for hole making (drilling, boring, tapping and reaming).

Although only hole making operations are considered in the first version of the APPG (APPG1), the module presents the capability of producing feasible non linear process plans for any existing part program. Indeed every time the APPG1 finds in the original sequential part program a milling operation, it maintains in the non linear process plans all the precedence constraints the milling operation has with all the other operations. Thus non linear process plans proposed by the APPG1 are sub-optimal, with reference to the whole number of alternative/parallel operations that can be derived by a human expert process planner, but they are feasible.

The capability of the APPG1 module in deriving sub-optimal but feasible solutions is a great advantage of the approach. Indeed the hole making APPG1 is able to process any complex part program composed of every type of operations and tools. Every time the APPG1 finds some operation/tool that it is not able to analyse, it leaves the precedence constraints as they were in the original part program.

3. The Precedence Constraints Elimination Module

3.1 Assumption of the Module

The core sub-module within APPG1, i.e. the module that contains all the knowledge and the logic required to eliminate precedence constraints, is the Precedence Constraints Elimination module (PCE).

Before starting with the description of the logic used by the PCE for breaking precedence constraints, it is necessary to describe the reference manufacturing system and the relevant assumptions adopted. The manufacturing system the PCE refers to, is an integrated and flexible manufacturing system, composed of CNC machining centres. Since every existing part program refers to a given positioning of the workpiece, the APPG1 will break precedence constraints for every set of operations related to a given positioning of the part. In other words, selection of the number and types of positioning required to obtain the finished part are considered fixed and are not changed by the APPG1 module.

In order to describe how the PCE analyses and decides to break precedence constraints, the different categories of precedence constraints can be classified in the following way [6]:

1. dimensions with a datum as anteriority,
2. geometric tolerances with data references as anteriorities,
3. technological constraints in order to execute sequence of operations properly,
4. economic constraints which reduce production costs and wear or breakage of costly tools.

Considering the manufacturing system the APPG1 refers to, only the third type of constraints, the technological ones, must be considered.

The first type of constraints is not required because when machining a surface, the only reference datum for a CNC machine is the workpiece zero adopted in the positioning considered.

For this last reason and since all the features are machined without changing positioning and/or machine, also the second type of precedence constraints has not to be considered. Finally the fourth type of precedence constraints is not considered within APPG1 because the aim of the module is not to optimise (by deriving the best solution to operations sequencing) but to increase the number of possible process plans which can be adopted to machine the part. Every type of economic consideration is indeed postponed to real time process control phase, on the basis of resources availability, dynamic bottlenecks, priority of part, etc.

Therefore the only precedence constraints the PCE module has to deal with are the technological ones.

3.2 General Architecture of the PCE Module

In order to remove precedence constraints that are not technological ones, the PCE module has to execute a sequence of steps that are summarised in Figure 2. For a given positioning of the part, the part program reports the sequence in which operations have to be executed. Since part programs report an ordered set of tool paths, either in cutting or rapid speed, the first step that the PCE module has to deal with is to cluster tool paths into operations. An operation is, in this framework, the set of CNC instructions required to realise an *Elementary machined surface* (*EMS*). The *EMS* is the surface generated by the cutting movement of a tool. Consider for instance the drilling operation represented in Figure 3, in order to machine the hole, the tool executes movements 1, 3 and 4 in rapid speed, while only movement 2, executed in cutting speed, is directly related with the feature machined.

When all the information coming from the Part Program Interpreter has been loaded, the PCE recognises operations by clustering together instructions (tool paths) between two rapid movements[1].

When the clustering phase is completed, the PCE module starts analyse precedence constraints among the n operations, in order to remove all the ones that are not necessary. The constraints are represented by means of two attributes for each operation. Consider for instance the i^{th} operation:

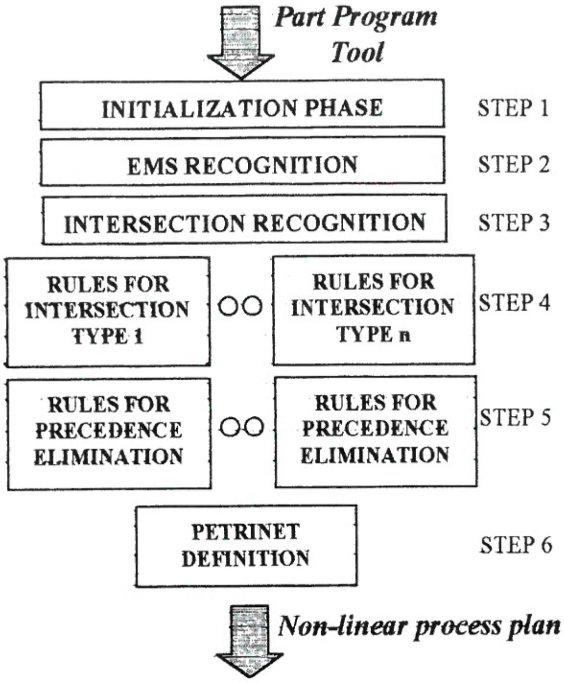

Figure 2. The Architecture of the PCE Module

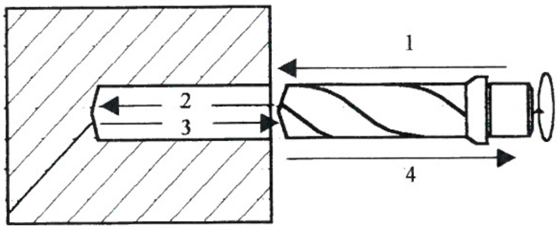

Figure 3. Tool Movements in A Hole Making Operation

- PRE (i) *is the attribute that contains links to operations that have to be executed before operation* i;
- POST (i) *is the attribute that contains links to operations that have to be executed after operation* i.

At the beginning the two attributes are set as follows:

- *PRE (i)*=1, 2, .., i-1;
- *POST (i)*= i+1, i+2, .., n.

This assignment means that all the operations that precede operation i in the original sequence have a precedence constraint on the operation i. Similarly, operation i has a precedence constraint on all the operations that, in the original part program, appear after operation i.

The PCE is now ready to start break constraints that are not technological ones.

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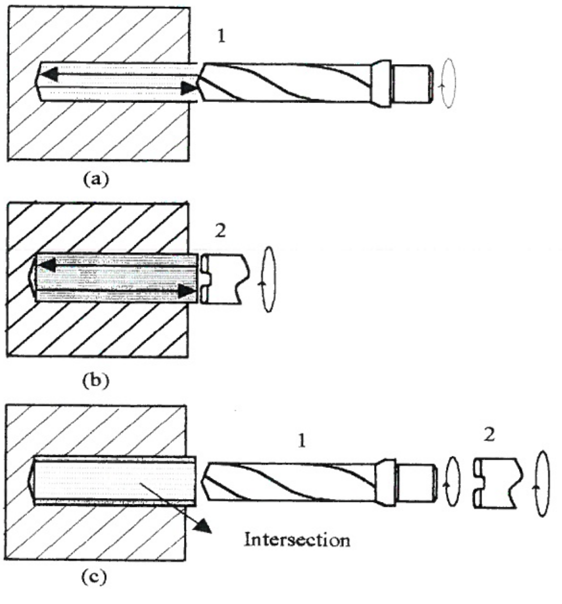
[1] The PCE module is also able to recognise that when two rapid movements are contiguous, there is no operation to define.

In order to define technological rules for precedence constraint elimination, expert process planners have been interviewed. Since the positioning is fixed and the machine working the part is assumed to be the same during the whole process plan, all the constraints that are related to assuming a surface as datum are not necessary. Therefore the PCE module considers two main situations:

1. constraints between rough cutting operations and finishing ones, in order to obtain a given feature;
2. constraints between operations that, executed in reverse order, can affect the surface quality or the tolerance of the related surface.

As an example of the first situation, consider machining of a hole that requires a finished surface (Figure 4). This operation is generally executed in two steps: the first is a rough drilling operation (Figure 4 (a)), the second one is a finishing boring (Figure 4 (b)). By considering the volumes swept by the two tools during their cutting movements, it is possible to observe an intersection between the two volumes (Figure 4 (c)). Therefore in this example the intersection between volumes can be related to a precedence constraint that cannot be eliminated, i.e. the sequence of operations is fixed.



(a)

(b)

(c)

Figure 4. Rough and Finishing Cutting of A Hole: Intersections Between *EMSs*

As an example of the second type of constraints, consider the two holes represented in Figure 5. If a hole requires a tight tolerance and the tool machining the hole can have a straightness problem (for instance an HSS drill), it has to be machined before the other interacting hole.

As it can be observed, also this second situation is characterised by an intersection between the volumes generated by the two tools during their cutting movements.

These two examples are instances of a general basic rule that has been validated by considering expert process planners knowledge and that acts as the basis of PCE approach:

"Technological precedence constraints are always related to interacting Elementary Machined Surfaces".

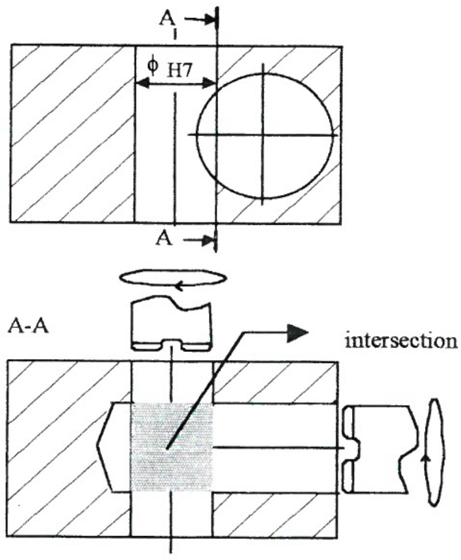


Figure 5. Intersection Between Holes With Perpendicular Axis

Therefore in the third phase, the PCE module searches for intersections among operations. Any couple of operations is analysed in order to find intersections between the Elementary Machined Surfaces (*EMS*s). If two *EMS*s do not present intersection, the PCE module removes the precedence constraint. This task is executed by using a solid modeler module that acts as geometric calculator. For every couple of *EMS*s that presents an intersection, the intersection type is recognised (Figure 6 reports the types of intersections considered in the approach) and the set of rules related to the specific intersection type is executed, in oder to break precedence constraints.

The reason why PCE considers separately the different types of intersection is due to different

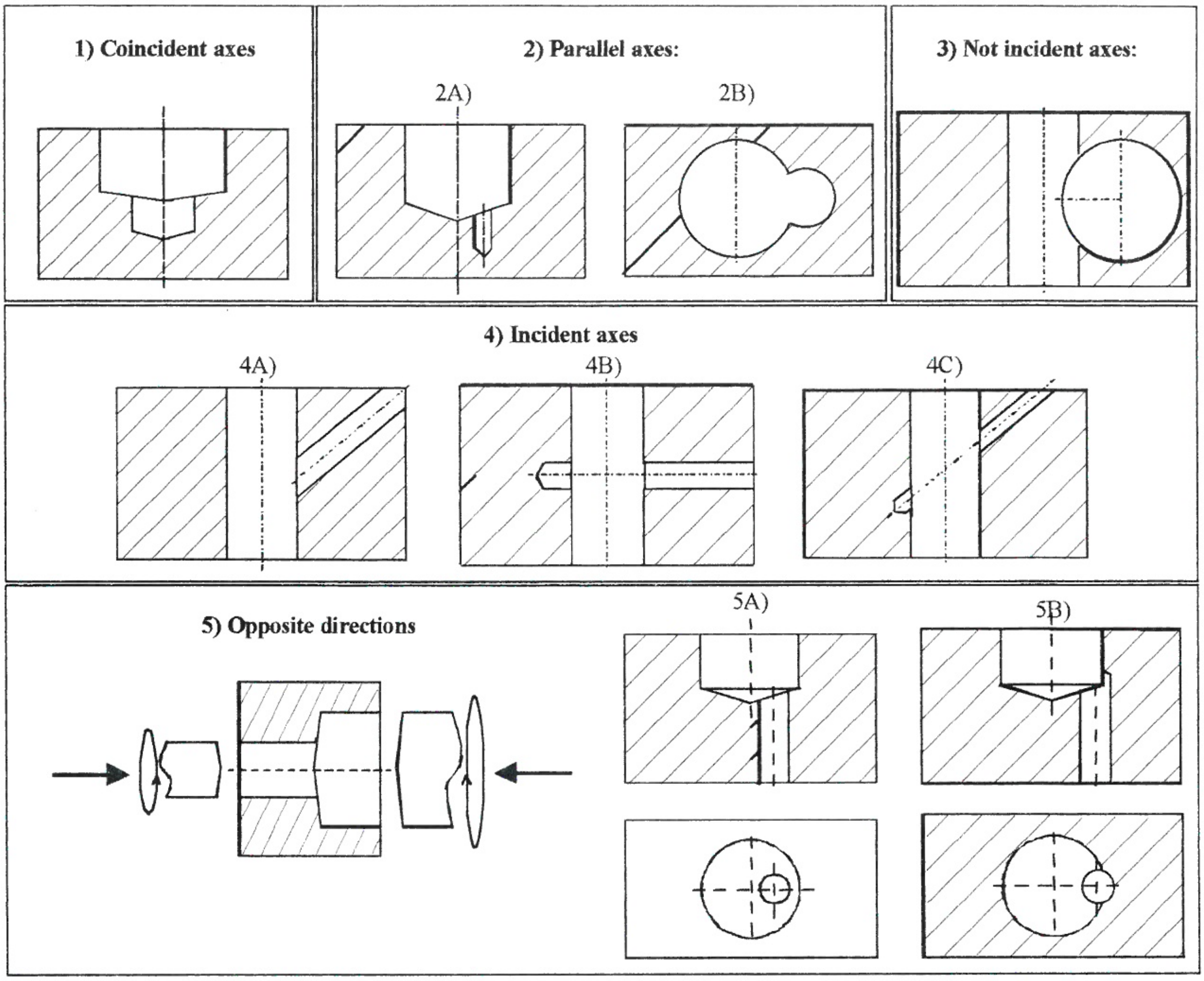


Figure 6. Types of Intersections Between Holes

technological problems each intersection type calls for. An example of technological rule for a given intersection type is reported in the following Section.

Once the intersection type has been recognised and the relative rules for precedence constraints elimination have been considered, the PCE updates the PRE and POST attributes for each operation. At the end of this phase, the alternative process plan is generated and given as output of the module in the form of a Petri net [9-10].

3.3 Examples of Rules for Precedence Constraints Elimination

In order to give an idea of technological rules implemented in the PCE module, some rules related to the first two cases represented in Figure 6 (cases 1 and 2 A) are described in the following Subsections.

3.3.1 Example 1. Coaxial Holes

Consider two drilling operations: the geometry realised by the tools used in these operations can be the one represented in Figure 7 (I) or the other represented in Figure 8 (II). The two situations will be referred to as, respectively, I

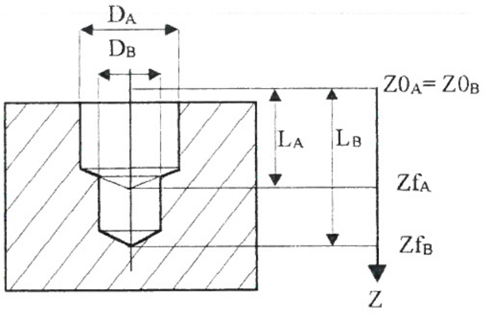


Figure 7. I Geometry

and II geometry. Since in both cases the volumes swept by the two tools intersect, it is not possible to simply remove the precedence constraints but some additional reasoning must be carried out.

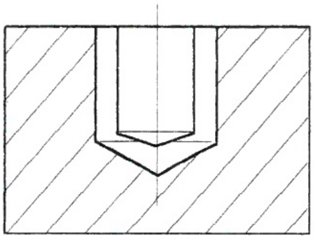


Figure 8. II Geometry

In order to remove the precedence constraint, one condition must be respected, regardless the geometry characterising the two coaxial drilling operations. With reference to the sequence in which the two *EMS*s (Elementary Machined Surfaces) are realised in the original part program, in order to eliminate the precedence constraint, the tool used in the second operation must be able to centre.

This condition is required to avoid problems in a situation in which the first tool acts as centrum drill for the second one. Indeed if the second tool is not able to centre, the sequence cannot be changed, i.e. the precedence constraint cannot be removed. Then the rule adopted in this case is:

If *the tool related to the second drilling operation is not able to centre,*

then *do not remove the precedence constraint.*

In order to really break the precedence constraint, other conditions must be respected, depending on the geometry realised by the two tools.

3.3.1.1 Geometry I

With reference to the geometry I represented in Figure 7, two situations may occur:

1. Hole A is machined before hole B (Figure 9);
2. Hole B is machined before hole A (Figure 11).

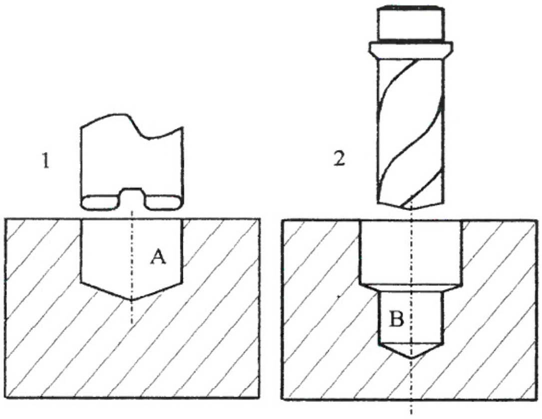


Figure 9

Consider the first situation, represented in Figure 9. If the precedence constraint is removed, i.e. the sequence is changed, the cutting length of tool 2 could not be sufficient to machine hole B along all its length L_B (Figure 10).

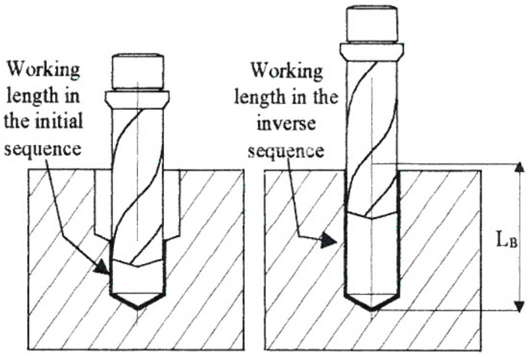


Figure 10

Another problem that could arise if the sequence were changed is related with the tool path tool 2 could have in the original sequence. Indeed it is possible that in the original part program, tool 2 enters the bigger diameter hole in rapid speed. If this situation occurs, the precedence constraint could be eliminated but the PCE module notifies an alarm and suggests to change the ISO code in order to remove precedence constraint.

The two situations described are summarised in the following rule:

When hole A is machined before hole B:

If *tool 2 has the required cutting length,* ***then*** *remove the precedence constraint* ***and***

if $ZO_A \leq ZO_B$ *(Figure 7)* , ***then*** *issue a warning regarding ISO code changes needed.*

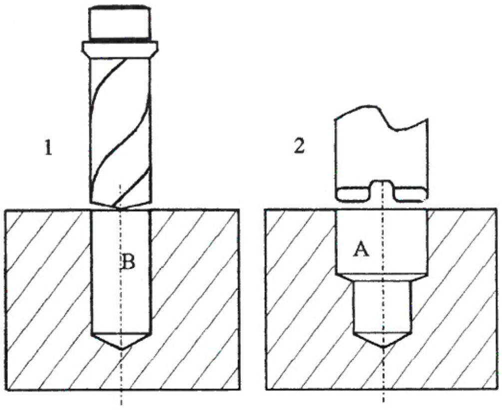


Figure 11

Consider now the second situation in which hole B is machined before hole A (Figure 11).

Since the precedence constraint can be eliminated without affecting the *EMS*s machined, the rule in this second situation is the following:

If *hole B is machined before hole A,*

then *remove the precedence constraint.*

3.3.1.2 Geometry II

If the second geometry is realised, (Figure 8) sequence may not be changed because the first tool acts as rough cutting for the second one. Then the rule in this situation is:

If *geometry II is realised by the two tools,*

then *do not remove the precedence constraint.*

3.3.2 Example 2. Holes With Parallel Axis

Consider the situation represented in Figure 12: there are two holes that have parallel axis. The volume swept by the drill machining one hole is also included, for a given length, in the volume swept by the tool machining the other hole.

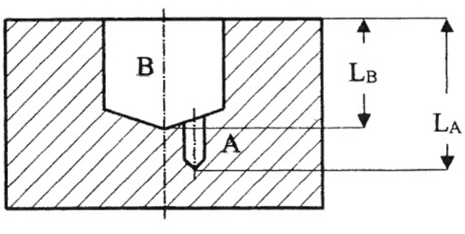


Figure 12

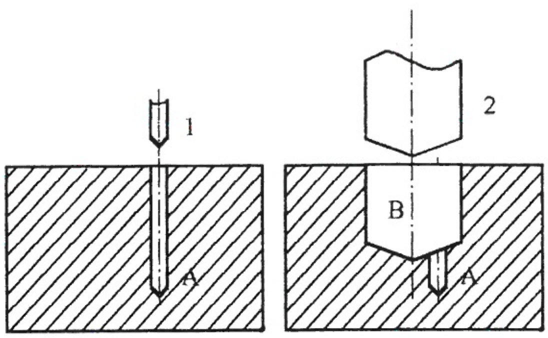


Figure 13

Two situations may occur in the original part program's sequence:

1. Hole A is machined before hole B (Figure 13);
2. Hole B is machined before hole A (Figure 16).

If the first situation occurs, the technological rule is:

If *L_A is smaller than L_B (Figure 12)* ***and,***

considering the whole set of operations, tool 1 acts as centrum drill for another tool,

then *do not remove the precedence constraint.*

The condition imposed by the rule is related to the possibility that tool 1 acts as centrum drill for a different coaxial hole. Indeed consider the case in which hole A is machined before hole B and $L_A < L_B$ (Figure 14). If the precedence constraint is removed, hole A is never machined, because hole B is executed firstly and it includes the other *EMS*.

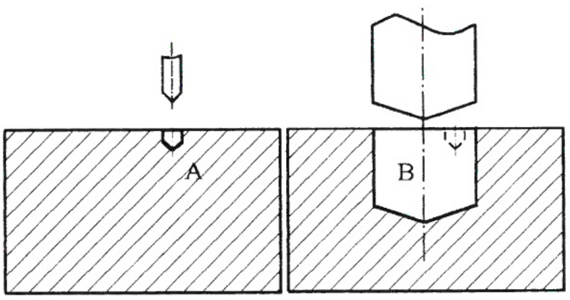


Figure 14

This inverted sequence could cause problems when hole A acts as centrum hole for another tool. Consider indeed the sequence of

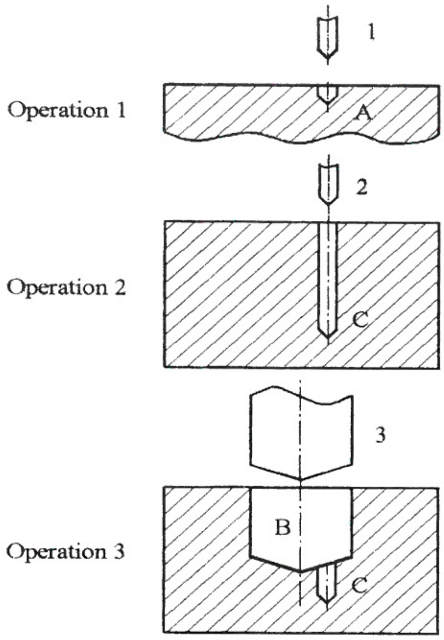


Figure 15

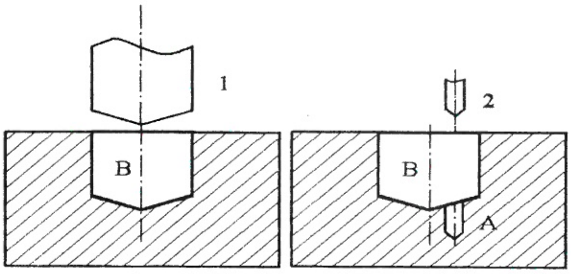


Figure 16

operations represented in Figure 15: the two holes directly considered in the rule are A and B, while the third hole which could have straightness problem is hole C. In this situation, the first drill acts as centrum drill for tool 2. If the sequence is changed (tool 3 machines before tool 1), since there is no centrum hole for tool 2, this tool will not work properly.

Consider now the second situation, namely hole B is machined before hole A (Figure 16), the technological rule in this case is:

If:

i. *tool 2, during its cutting movement, intersects the axis of the hole machined by tool 1 or*

ii. *tool 2 has a cutting length equal to or greater than L_A (Figure 12),*

***then** remove the precedence constraint.*

The first condition is related to straightness problems tool 2 could have in working on a pre-existing non coaxial hole (Figure 17).

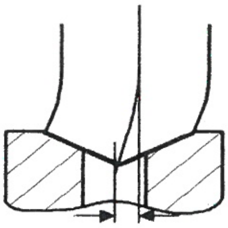


Figure 17

The second condition is related to the fact that if tool 2 works before tool 1, it has to machine along all L_A (this situation is similar to the one described in Example 1, Figure 10).

4. Validation Phase

In order to validate the APPG1 module capability in breaking precedence constraints that are not technological ones, a real case, extracted by the part mix processed by Lajous Industries (F), has been used. The workpiece to machine is a bracket, a component for the automotive industry.

It has been considered the first positioning required to machine the part (Figure 18) and the relative part program has been processed by the APPG1 module. The same sequence of operations has been submitted to expert process planners asking them for a manual definition of the alternative process plan.

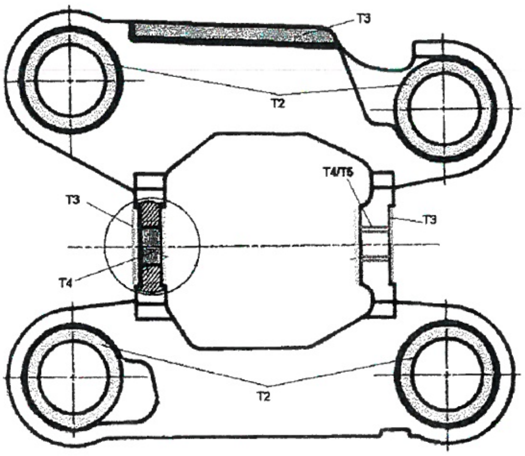


Figure 18. The Real Case

Results are reported in Figure 19. In order to represent non linear process plans, a Petri net notation has been used [9-10].

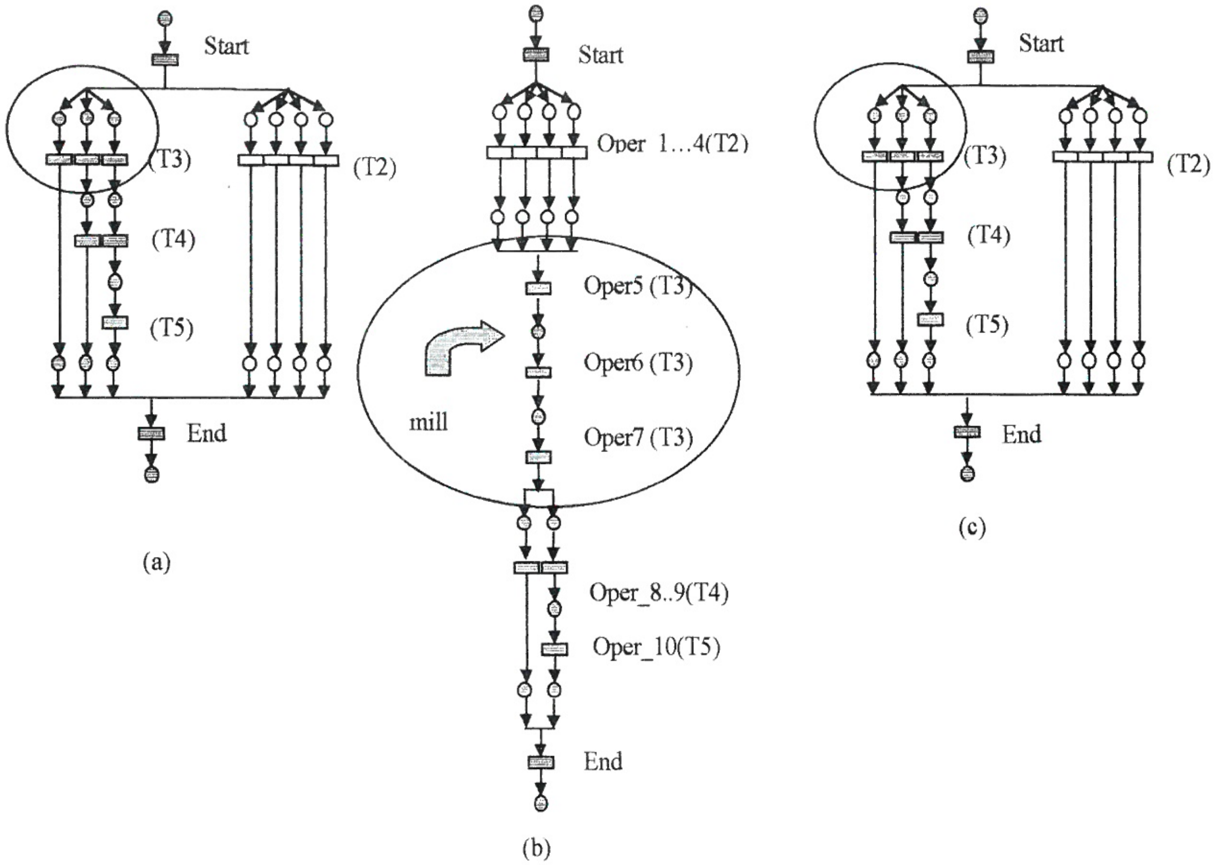


Figure 19. Petri Nets Generated By Expert Process Planners (a), APPG1 Software (b) and APPG1 Software Including Milling Operations (c)

As it can be observed the Petri nets (a) and (b) representing alternative process plans generated respectively by expert process planners and the APPG1 module, match together for hole making operations. The only set of operations that are not reported in the same order for the two Petri nets are the milling ones. Indeed, as mentioned in Subsection 3.1 "Assumption of the Module", milling operations are executed in the original order, maintaining all precedence constraints found in the sequence of the starting part program.

In order to analyse future capabilities of the approach, another Petri net in which also milling operations are partially considered, has been generated by the APPG1 (Figure 19 (c)). This second alternative process plan has been generated also considering intersections of swept volumes taking into account also milling operations. Every time no intersection is found between a milling operation and another operation, the relative precedence constraint is eliminated. If also a set of rules dealing with milling operations were implemented in the module, then further precedence constraint elimination could be in general carried out.

However, since most of precedence constraints elimination is due to surfaces that present no interaction, in the example the Petri net obtained with this partial modification (Figure 19 (c)) is identical to the one created by the expert process planners (Figure 19 (a)). This result seems to be very encouraging for the second phase of implementation in which also milling operations are considered. However the APPG1 that deals only with hole making operations is already able to derive sub-optimal but feasible solutions. In order to validate this conclusion, the approach has been tested using other existing part programs. The results obtained are similar to the ones reported in the example.

5. Conclusions

In order to exploit the advantages that non linear part programs can offer in manufacturing practice, a new approach, called APPG1, for translating standard linear part programs into non linear ones has been presented. Compared with results reported in the literature, the approach proposed is the first focusing on translating an existing part program, i.e. oriented to the reusability of part programs already developed. A considerable capability of the proposed approach is also related to its ability of deriving feasible non linear process plans, also when complex part programs or non -standard operations/tools are considered.

Results obtained by comparing non linear process plans generated by the APPG1 with the ones developed by expert human process planners are very encouraging in assessing the module as a viable solution for the introduction of non linear process plans in manufacturing practice.

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