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# APPLYING PRECEDENCE RELATIONSHIPS AND CAD/CAM SIMULATION IN TIME-BASED OPTIMIZATION OF PROCESS PLANNING

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**Abstract:**
Optimization of process planning belongs to the group of combinatorial optimization problems which at the macro and micro level consists of the selection of machining operations, definition of sequences of machining operations and their grouping into processes, selection of manufacturing resources, machining parameters and strategies. The objective function used for evaluating process plans is mostly defined by manufacturing cost, manufacturing time, surface quality and surface accuracy.
The main goal of this research refers to the process planning and optimization of manufacturing time by applying precedence relationships among machining operations, as well as the simulation technique within the CAD/CAM system. The precedence relationships are defined on the basis of dimensional, geometric, technological and economical precedence constraints. Based on these rules, precedence matrices for determining operation sequence for the given shaft part are formed, and afterwards, machining operations are grouped into appropriate processes. For the given rational variants of process plans, a simulation of machining process is performed within the Catia software system. The obtained output is the best variant of process plan for the shaft part on the basis of manufacturing time as the adopted objective function.

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## 1. INTRODUCTION

Production system will operate well, achieve growth and development only if market requirements are met, that is, if it produces usable, economical, well-designed, environmentally-friendly, competitive and marketable products [1].

Within production systems, a dominant role in meeting market requirements for novel and customized products belongs to processes of design, planning, control and manufacturing. Technological preparation of production as a function of production system represents the basic integrating component of the mentioned processes [2]. The basic task of the technological preparation of production is to study product design and manufacturing capabilities of a production system and according to that provide the best possible manufacturability of product design and determine the most effective manufacturing methods and techniques for rational utilization of manufacturing resources within the production process [3]. General model of technological preparation of production consisting of six stages is represented in the paper [4]. Fig.1 shows the activity tree of the model of technological preparation of production.

Two main tasks of the technological preparation of production are process planning and optimization of process plans. Process planning consists of conceptual and detailed process planning which is then divided into macro and micro process planning [3-5]. Generally, the detailed process planning is focused on many tasks, such as the selection and design of raw materials, feature recognition and extraction, definition of machining operations and their grouping into process operations, definition of process

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operations and their sequences, selection of machining and manufacturing systems, determination of machining allowances and appropriate tolerances, selection of technological bases and appropriate fixtures, selection of tooling, selection of measuring methods and approprate measuring instruments, selection of machining parameters and strategies, and so on [4,6]. Techno-economic optimization of process plans is concerned with finding the best solution for given conditions that are based on the technological and economical optimization criteria [3,7,8].

In practice, two approaches are usually applied in the macro process planning [4]:

1. The first or traditional approach comes down to the fact that based on the design and technological analysis of product characteristics machining surfaces are defined, then on the basis of experience, types and sequence of process operations are determined first, and types and sequences of machining operations with all the necessary information, such as manufacturing resources and machining parameters are defined afterwards; and,
2. The second approach is based on the recognition and extraction of features for which the possible machining operations with the necessary manufacturing resources and manufacturing parameters are defined, and then the sequence of machining operations are defined and later grouped into appropriate process operations.

The first approach is based on the individual process planning which greatly emphasizes the influence of a designer, and is significantly faster approach but does not offer great possibilities for optimization. The second approach provides considerably better possibilities for optimization and development of modern generative CAPP systems that are based on the application of feature technologies, methods of artificial intelligence, STEP standards and others [2-4].

The main subject and aim of this research is focused on the process planning and optimization of process plans on the basis of manufacturing time by applying precedence rules and the (CAD/CAM) computer simulation.

The second approach in process planning that is previously described will be applied in this paper. Firstly, manufacturing features will be defined for the given product, and later the possible machining operations, tools and other elements of machining system and process will be selected. Precedence rules among machining operations will be defined on the basis of dimensional, geometric, technological and economical precedences. Based on these rules precedence matrices will be formed from which the selection of variants of operation sequences and their grouping into process operations will be performed. Within these tasks, in addition to the selection of variants of machining operations, the selection of resources and machining parameters will also be done. Computer simulation of machining process of the adopted variants of process plans will be realized within the selected (CAD/CAM) system. Based on the realized simulation the most favorable variant will be selected in terms of manufacturing time as the objective function of optimization.

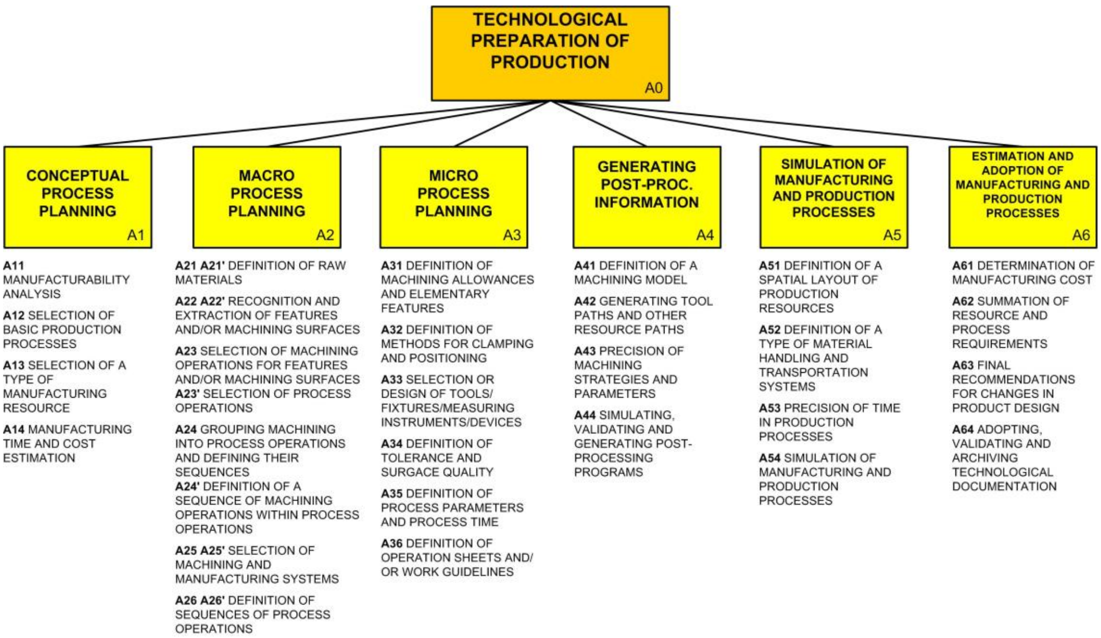


**Fig.1.** Activity tree of the model of technological preparation of production [4]

## 2. PRECEDENCE RULES AND COMPUTER SIMULATION IN PROCESS PLANNING AND OPTIMIZATION

### 2.1 Precedence rules in process planning and optimization

The problem of optimization of process planning, as the subject of this paper, is focused on two tasks within the process planning. The first task is to select and define machining operations for extracted manufacturing features, while the second one represents determination of optimal machining sequence of the given operations. The selection of machining operations is based on the feature geometry, technological requirement in terms of their machining and the determination of an appropriate machine, tool and tool approach direction that will provide good machining of manufacturing features. On the other side, the sequence of machining operations considers the optimal sequence (permutation) of operations which will be used to machine the given features without violating design and technological constraints that are provided on the drawing [9,10].

In terms of the selection of machining operations, machines, tools, fixtures, tool approach directions and determination of operation sequence, many authors define various "flexibilities" that have shown to be crucial for efficient production and the production system itself. According to the [10] these are the following types of flexibilities:

- process flexibility–the possibility of machining the same manufacturing feature using different machining operations or sequences of operations;
- machine flexibility-the possibility of performing the same manufacturing operation on different machines;
- tool flexibility-the possibility of performing the same manufacturing operation using different cutting tools;
- TAD (Tool approach direction) flexibility–the possibility of performing the same machining operation using different tool approach directions, or different types of setup; and,
- sequence flexibility–the possibility of changing the sequence of machining operations that are required for machining the given part.

Precedence relationships among machining operations represent a very significant element of process planning optimization and it directly depends on these rules whether the process plan will be valid or not. The precedence relationships, or precedence constraints, must be identified in order to verify the selected or randomly generated sequence of machining operations and to determine whether this sequence is feasible or not.

Two main groups of precedence relationships can be found in the literature [11]:

1) *Precedence relationships between the realizations of machining features*, which cover: fixture constraints, datum dependencies, parent-child dependencies, avoiding cutter damage, better machining efficiency.
2) *Precedence relationships among a set of different types of machining operations.*

For each set of machining operations for machining a feature there are fixed precedence relationships, such as the case when roughing operations come before finishing operations (e.g. drilling comes before reaming, milling comes before grinding etc.).

Precedence relationships among machining operations can be grouped on the basis of technical and economical constraints. According to that fact, the following groups of technical and economical constraints or so called precedences are defined [12]: dimensional precedence, geometric precedence, technological precedence and economical precedence.

***Dimensional precedence***. Determining precedence among machining operations due to dimensional reasons is related to surface dimensioning and can be defined in the form of the following rule: „Before machining a desired surface a surface related to whom the considered surface is dimensioned is machined first, and priorities have surfaces dimensioned in relation to a datum".

***Geometric precedence***. Determining priorities among machining operations due to geometric reasons is related to the requirements in terms of interaction between surfaces and axes, or so called position tolerances. In this case, precedence can be defined in the following form: „Surface related to whom the position tolerance of other surface is defined has the priority in machining".

***Technological precedence***. This group of constraints is mostly related to the precedence relationships among operations for machining a feature that do no require more machining operations (e.g. drilling before counter boring, counter boring before reaming, turning before grinding, etc.).

***Economical precedence.*** These constraints are, above all, related to reduction in manufacturing cost which is achieved by applying more productive or more economical method or a tool instead of less productive or less economical method or a tool.

### 2.2 Computer simulation in process planning and optimization

A term simulation in technics is most often understood as a technique of development and realization of a model of a real object or a system, with the purpose of studying behavior of that object or system without disturbing its environment. Simulation represents a process that is a copy or a parallel of a real process. Simulation covers a wide range of methods and softwares that mimic a real system. They are mostly realized using computers and appropriate computer programs and simulation systems. A modern simulation can be presented as an experiment conducted on a computer. Basically, a simulation includes three elements: real system, model and a simulation [13].

Modern CAD/CAM software systems that provide a simulation of machining processes are especially significant in process planning which is realized on CNC machining systems. By simulating machining processes, i.e. tool paths, it is also possible to avoid collisions between tools and work-holders, machine components, workpieces, etc. Simulation of machining processes provides the possibility to determine optimal tool type and tool path, then optimal operation type and operation sequence on the basis of manufacturing time [4,7]. Based on the literature analysis in this field, researchers have primarily dealt with the problem of optimization of process plans with the focus on prismatic parts [9,14]. Some authors, such as those in [12,15,16], considered rotationally-symmetric parts in their papers. This paper will consider the application of precedence relationships and the (CAD/CAM) simulation technique in process planning optimization for the adopted shaft, as a sample of rotationally-symmetric part.

## 3. PROCESS PLANNING AND OPTIMIZATION FOR A SHAFT PART

### 3.1 Input data

Basic input data for process planning activities are: part drawing with all the neseccary information, production volume in time units/production type and the available manufacturing equipment (machine tools, tools, fixtures, etc.) [4].

Fig.2 shows the 3D model of a shaft made of steel E335 which is used for optimization and whose drawing was taken from the paper [15].

For the given production volume of 1.500 parts per year, a hot rolled bar with Ø23 in diameter and 84 mm in length after cutting is used as a rational type of raw material.

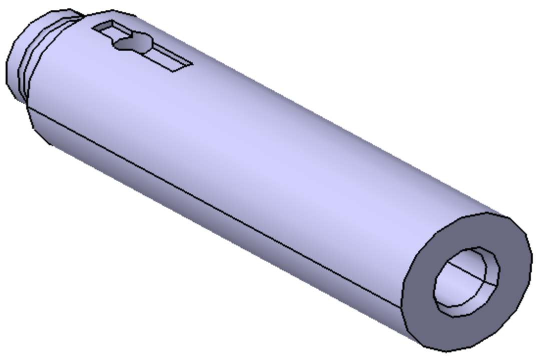

**Fig.2.** 3D model of a shaft

### 3.2 Defining machining features and variants of sequences and tools

By analyzing design and technological characteristics of the shaft elementary features were extracted and shown in (Fig.3).

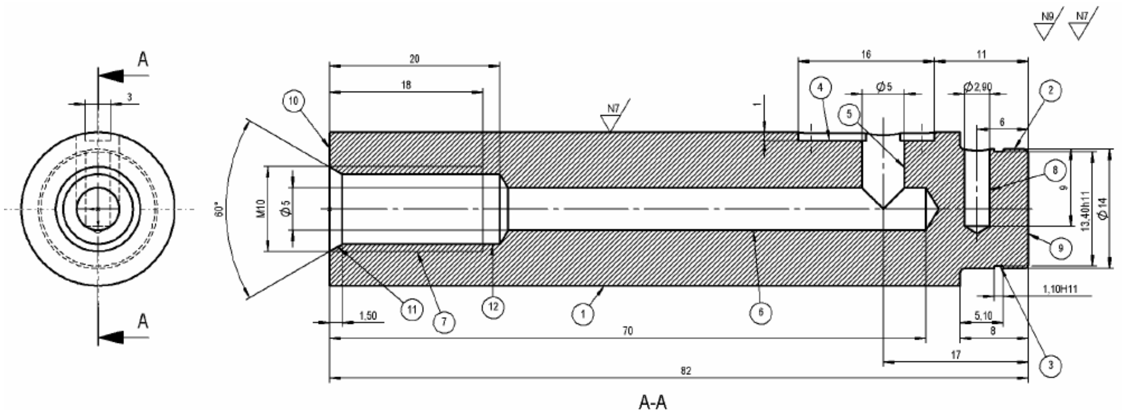


**Fig.3.** 2D drawing of a shaft with the extracted elementary features

Defined IDs of these features with description of their characteristics are given in the (table 1).

**Table 1.** Description of the extracted elementary features for the given workpiece - shaft

| Feature (F) | Name | Dimensions [mm] | Surface quality |
|---|---|---|---|
| F1 | Cylindrical surface | Ø20h8 x 74 | N7 |
| F2 | Cylindrical surface | Ø14 x 8 | N9 |
| F3 | Slot | Ø13,4h11x1.1H11 | N9 |
| F4 | Slot for wedge | 3 x 16 x 1 | N9 |
| F5 | Hole | Ø5 x9 | N9 |
| F6 | Hole | Ø5 x 70 | N9 |
| F7 | Internal thread | M10x1,5x18 | N9 |
| F8 | Hole | Ø2.9 x 9 | N9 |
| F9 | Face surface | Ø14 | N9 |
| F10 | Face surface | Ø20 | N9 |
| F11 | Countersink edges | 1.5 x 60° | N9 |
| F12 | Redrilling/Counterboring | Ø 8.5 x 20 | N9 |

Table 2 gives the recommended machining operations for the given features as well as the appropriate tools.

**Table 2.** Recommended machining operations and cutting tools for the extracted features

| F | Rough machining | Finish machining |
|---|---|---|
| F1 | **Rough turning/** Tool for rough longitudinal turning | **Finish turning/** Tool for finish turning |
| F2 | **Rough turning /** Tool for rough longitudinal turning | - |
| F3 | **Parting/**Tool for parting | - |
| F4 | **Milling/**End mill cutter≤Ø3 | - |
| F5 | **Drilling/**Center drill | - |
| | **Drilling/**Drill Ø5 | |
| F6 | **Drilling/**Center drill | - |
| | **Drilling/**Drill Ø5 | |
| F7 | **Threading/** Machining taps M10x1,5 | - |
| F8 | **Drilling/**Center drill | - |
| | **Drilling/**Drill Ø2,9 | |
| F9 | **Rough face turning/** Tool for rough facing turning | - |
| F10 | **Rough face turning/** Tool for rough facing turning | - |
| F11 | **Countersink/**Conical countersink | - |
| F12 | **Redrilling/**Drill Ø8,5 **Boring**/Counterboring Ø8,5 | - |

Cutting tools are chosen from the tool manufacturer catalogue Sandvik Coromant, as well as on the basis of (ISO/SRPS) standards, (table 3).

Based on the specific machining operations and selected tools from the mentioned catalogue and standards, the appropriate tools for performing machining operations as well as the *tool approach directions* (TADs) are defined and shown in (table 4).

According to the precedence rules which include *dimensional, technological, geometric and economical precedence*, the following precedence relationships are defined and shown in (table 5).

**Table 3.** Defined cutting tools for performing machining operations

| Tool ID (T) | Tool name | Tool specification (Sandvik Coromant) |
|---|---|---|
| T01 | Tool for rough turning | DCLNR/L-16 16 H12 CNMG 12 04 12-PR |
| T02 | Tool for finish turning | DDJNR/L 16 16 H11 DNMX 11 04 04 – WF |
| T03 | Center drill | Ø2,5 JUS K.03.061 |
| T04 | Drill Ø5 | R850-0500-70-A1A |
| T05 | Drill Ø7 | R840-0300-70-A0A |
| T06 | Chamfering endmill | R215.94-01500-AC74G |
| T07 | Machining tap M10x1 | R217.14C075150AK21N |
| T08 | End mill cutter Ø2 | R216.32-02030-AC60P |
| T09 | Drill Ø5 | R840-0300-50-A0A |
| T010 | Drill Ø2,9 | R840-0290-50-A0B |
| T011 | Parting tool | N123T3-0100-0000-CS |
| T012 | Drill Ø8,5 | R840-0850-x0-AyA |

**Table 4.** Defined cutting tool and TAD candidates for the given machining operations

| F | Feature name | Tool candidate | TAD candidate |
|---|---|---|---|
| F1 | Rough turning right side **(OP1)** | T01 | -z,-x |
| | Finish turning right side **(OP2)** | T02 | -z,-x |
| | Rough turning right side **(OP3)** | T01 | -z,-x |
| | Finish turning right side **(OP4)** | T02 | -z,-x |
| F2 | Rough turning **(OP5)** | T01 | -z,-x |
| F3 | Parting groove **(OP6)** | T011 | +z, -z |
| F4 | Milling groove **(OP7)** | T08 | -z |
| F5 | Center drill **(OP8)** | T03 | -z |
| | Drilling **(OP9)** | T09 | -z |
| F6 | Center drill**(OP8)** | T03 | -x |
| | Deep drilling **(OP10)** | T04 | -x |
| F7 | Threading **(OP11)** | T07 | -x |
| F8 | Center drill **(OP13)** | T03 | -z |
| | Deep drilling **(OP14)** | T010 | -z |
| F9 | Face turning **(OP15)** | T01 | +z, -z |
| F10 | Face turning **(OP16)** | T01 | +z, -z |
| F11 | Conical countersink **(OP17)** | T06 | -x |
| F12 | Redrill **(OP18)** | T012 | -x |

**Table 5.** Precedence relationships among operations

| OP | Precedence types | | | |
|---|---|---|---|---|
| | Dimensional | Technological | Geometrical | Economical |
| OP1 | | OP15 | | |
| OP2 | | OP1, OP15 | | OP5 |
| OP3 | | OP16 | | |
| OP4 | | OP3, OP16 | | |
| OP5 | OP15 | OP1 | | |
| OP6 | OP15 | OP1, OP5 | | |
| OP7 | OP15 | OP1, OP2 | | |
| OP8 | OP15 | OP1, OP2, OP7 | | |
| OP9 | OP15 | OP1, OP2, OP7, OP8, OP10, OP11 | | |
| OP10 | | OP16 | | |
| OP11 | OP16 | OP10 | | |
| OP12 | OP16 | OP10, OP11, OP17, OP18 | | |
| OP13 | OP15 | OP1, OP2 ,OP5 | | |
| OP14 | OP15 | OP1, OP2, OP5, OP13 | | |
| OP15 | | | | |
| OP16 | | | | |
| OP17 | OP15 | OP10, OP11, OP18 | | |
| OP18 | OP15 | OP10, OP11 | | |

Based on the precedence relationships, precedence matrix for the given machining operations is defined and represented in (Fig.4).

| OP | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | | | | X | | | |
| 2 | X | | | | X | | | | | | | | | | X | | | |
| 3 | | | | | | | | | | | | | | | | X | | |
| 4 | | | X | | | | | | | | | | | | | X | | |
| 5 | X | | | | | | | | | | | | | | X | | | |
| 6 | X | | | | X | | | | | | | | | | X | | | |
| 7 | X | X | | | | | | | | | | | | | X | X | | |
| 8 | X | X | | | | | X | | | | | | | | X | X | | |
| 9 | X | X | | | | | X | X | | X | X | | | | X | X | | |
| 10 | | | | | | | | | | | | | | | | X | | |
| 11 | | | | | | | | | | X | | | | | | X | | |
| 12 | | | | | | | | | | X | X | | | | | X | X | X |
| 13 | X | X | | | | X | | | | | | | | | X | | | |
| 14 | X | X | | | X | | | | | | | | X | | X | | | |
| 15 | | | | | | | | | | | | | | | | | | |
| 16 | | | | | | | | | | | | | | | | | | |
| 17 | | | | | | | | | | X | X | | | | X | | | X |
| 18 | | | | | | | | | | X | X | | | | X | | | |

**Fig.4.** The precedence matrix for machining operations

### 3.3 Grouping machining operations into process operations/setups

In order to define possible variants of process plans for machining the represented shaft model, it is necessary to group machining operations into appropriate process operations, i.e. setups.

By analyzing the provided machining operations, it can be concluded that the main type of machining operation for both variants is turning in its appropriate setups.

The following text provides variants of machining sequences based on the previously defined precedence matrix and variants of machining operations. Fig.5 and 6 represent two adopted variants of possible machining sequence and their grouping into the appropriate setups. In this case, those variants are called "variant 1" and "variant 2".

| OP | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | | | | X | | | | | 1 | OP1 | | | | | | | | | | | | | | | | |
| 2 | X | | | | X | | | | | | | | | | X | | | | | 3 | 2 | 1 | / | / | / | / | / | / | / | / | OP2 | | | | | | |
| 3 | | | | | | | | | | | | | | | | X | | | | 1 | 1 | 1 | 1 | OP3 | | | | | | | | | | | | | |
| 4 | | | X | | | | | | | | | | | | | X | | | | 2 | 2 | 2 | 2 | 1 | OP4 | | | | | | | | | | | | |
| 5 | X | | | | | | | | | | | | | | X | | | | | 2 | 1 | OP5 | | | | | | | | | | | | | | | |
| 6 | X | | | | X | | | | | | | | | | X | | | | | 3 | 2 | 1 | / | / | / | / | / | / | / | / | / | / | / | / | / | / | OP6 |
| 7 | X | X | | | | | | | | | | | | | X | X | | | | 3 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | OP7 | | | | | |
| 8 | X | X | | | | | X | | | | | | | | X | X | | | | 4 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | OP8 | | | | |
| 9 | X | X | | | | | X | X | | X | X | | | | X | X | | | | 7 | 6 | 5 | 5 | 5 | 5 | 5 | 4 | 3 | 3 | 3 | 3 | 2 | 1 | OP9 | | | |
| 10 | | | | | | | | | | | | | | | | X | | | | 1 | 1 | 1 | 1 | 1 | 1 | OP10 | | | | | | | | | | | |
| 11 | | | | | | | | | | X | | | | | | X | | | | 2 | 2 | 2 | 2 | 1 | 1 | 1 | OP14 | | | | | | | | | | |
| 12 | | | | | | | | | | X | X | | | | | X | X | X | | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 3 | 2 | 1 | OP12 | | | | | | | |
| 13 | X | X | | | | | | | | | | | | | X | | | | | 4 | 3 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | / | / | / | OP13 | | |
| 14 | X | X | | | | | | | | | | | X | | X | | | | | 5 | 4 | 3 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | / | / | / | / | OP14 | |
| 15 | | | | | | | | | | | | | | | | | | | | OP15 | | | | | | | | | | | | | | | | | |
| 16 | | | | | | | | | | | | | | | | | | | | / | / | / | OP16 | | | | | | | | | | | | | | |
| 17 | | | | | | | | | | X | X | | | | X | | | X | | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 1 | OP17 | | | | | | | | |
| 18 | | | | | | | | | | X | X | | | | X | | | | | 3 | 2 | 2 | 2 | 1 | 1 | 1 | / | OP18 | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | OP15 | OP1 | OP5 | OP16 | OP3 | OP4 | OP10 | OP11 | OP18 | OP17 | OP12 | OP2 | OP7 | OP8 | OP9 | OP13 | OP14 | OP6 |
| | | | | | | | | | | | | | | | | Process | | | | 20/1 | | | 20/2 | | | | | | | | 20/3 | | | | | | |

**Fig.5.** Generated sequence of machining operations and their grouping into 3 setups (20/1, 20/2 and 20/3)–variant 1

| OP | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | | | | X | | | | | 1 | 1 | 1 | OP1 | | | | | | | | | | | | | | |
| 2 | X | | | | X | | | | | | | | | | X | | | | | 3 | 3 | 3 | 2 | 1 | OP2 | | | | | | | | | | | | |
| 3 | | | | | | | | | | | | | | | | X | | | | 1 | OP3 | | | | | | | | | | | | | | | | |
| 4 | | | X | | | | | | | | | | | | | X | | | | 2 | 1 | / | / | / | / | / | OP4 | | | | | | | | | | |
| 5 | X | | | | | | | | | | | | | | X | | | | | 2 | 2 | 2 | 1 | OP5 | | | | | | | | | | | | | |
| 6 | X | | | | X | | | | | | | | | | X | | | | | 3 | 3 | 3 | 2 | 1 | / | OP6 | | | | | | | | | | | |
| 7 | X | X | | | | | | | | | | | | | X | X | | | | 3 | 3 | 3 | 2 | 1 | 1 | / | / | / | / | / | / | / | OP7 | | | | |
| 8 | X | X | | | | | X | | | | | | | | X | X | | | | 4 | 4 | 4 | 3 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | OP8 | | | |
| 9 | X | X | | | | | X | X | | X | X | | | | X | X | | | | 7 | 7 | 7 | 6 | 5 | 5 | 4 | 4 | 4 | 3 | 2 | 2 | 2 | 2 | 1 | OP9 | | |
| 10 | | | | | | | | | | | | | | | | X | | | | 1 | / | / | / | / | / | / | / | OP10 | | | | | | | | | |
| 11 | | | | | | | | | | X | | | | | | X | | | | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | OP11 | | | | | | | | |
| 12 | | | | | | | | | | X | X | | | | | X | X | X | | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 2 | 1 | OP12 | | | | | |
| 13 | X | X | | | | | | | | | | | | | | | | | | 4 | 4 | 4 | 3 | 2 | 2 | 1 | / | / | / | / | / | / | / | / | / | OP13 | |
| 14 | X | X | | | | | | | | | | | X | | | | | | | 5 | 5 | 5 | 4 | 3 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | OP14 |
| 15 | | | | | | | | | | | | | | | | | | | | / | / | OP15 | | | | | | | | | | | | | | | |
| 16 | | | | | | | | | | | | | | | | | | | | OP16 | | | | | | | | | | | | | | | | | |
| 17 | | | | | | | | | | X | X | | | | X | | | X | | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 1 | OP17 | | | | | | |
| 18 | | | | | | | | | | X | X | | | | X | | | | | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | OP18 | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | OP16 | OP3 | OP15 | OP1 | OP5 | OP2 | OP6 | OP4 | OP10 | OP11 | OP18 | OP17 | OP12 | OP7 | OP8 | OP9 | OP13 | OP14 |
| | | | | | | | | | | | | | | | | Process | | | | 20/1 | | 20/2 | | | | | 20/3 | | | | | | 20/4 | | | | |

**Fig.6.** Generated sequence of machining operations and their grouping into 4 setups (20/1, 20/2, 20/3 and 20/4) – variant 2

Table 6 and 7 give a more detailed representation of grouped machining operations for both variants. For the given machining sequence, the tools previously defined in the (table 4) are used.

**Table 6.** Variant 1 of machining operations

| Operation: Turning | |
|---|---|
| **Sub operation** | **ID operation** |
| 20/1 | OP15 , OP1 , OP5 |
| 20/2 | OP16 , OP3 , OP4 , OP10 , OP11 , OP18 , OP17 ,OP12 |
| 20/3 | OP2 , OP7 , OP8 , OP9 , OP13 , OP14 , OP6 |

**Table 7.** Variant 2 of machining operations

| Operation: Turning | |
|---|---|
| **Sub operation** | **ID operation** |
| 20/1 | OP16, OP3 |
| 20/2 | OP15, OP1, OP5, OP2, OP6 |
| 20/3 | OP4, OP10, OP11, OP18, OP17, OP12 |
| 20/4 | OP7, OP8, OP9, OP13, OP14 |

### 3.4 Simulation of the adopted variants of process plans within the CAD/CAM software

The Catia software system is adopted as (CAD/CAM) software for modelling and simulation of process plans. The choice of cutting conditions is realized in two ways. The first way is based on the recommendations from the previously mentioned tool catalogue, while the second one is based on the general recommendations from the machining technology manual.

Table 8 shows the simulation times for each machining operation in variant 1 on the basis of the adopted cutting conditions from the mentioned catalog. Table 9 summarizes the obtained results for both variants of process plans and for both ways of choosing cutting conditions.

**Table 8.** Times for the variant 1 with the recommended cutting conditions by the tool manufacturer

| Operation | Machining time [min] | Total time [min] |
|---|---|---|
| **OP15** | 00:00:14 | 00:00:22 |
| **OP1, OP5** | 00:00:34 | 00:00:44 |
| **OP16** | 00:00:10 | 00:00:17 |
| **OP3** | 00:00:16 | 00:00:16 |
| **OP4** | 00:00:08 | 00:00:13 |
| **OP10** | 00:00:03 | 00:00:08 |
| **OP11** | 00:02:33 | 00:02:33 |
| **OP18** | 00:00:06 | 00:00:07 |
| **OP17** | 00:00:04 | 00:00:04 |
| **OP12** | 00:00:06 | 00:00:06 |
| **OP2** | 00:00:05 | 00:00:21 |
| **OP7** | 00:00:24 | 00:00:31 |
| **OP8** | 00:00:04 | 00:00:05 |
| **OP9** | 00:00:07 | 00:00:10 |
| **OP13** | 00:00:03 | 00:00:07 |
| **OP14** | 00:00:06 | 00:00:08 |
| **OP6** | 00:00:03 | 00:00:05 |
| **Σ** | **5:06 [min]** | **6:17 [min]** |

**Table 9.** Machining time for both variants of process plans and both ways of choosing cutting conditions

| Variants TP/ Choose of cutting condition | Machining time [min] | Total time [min] |
|---|---|---|
| Var I/ Choose 1 | 5:06 | 6:17 |
| Var I/ Choose 2 | 5:46 | 8:20 |
| Var II/ Choose 1 | 5:16 | 6:50 |
| Var II/Choice 2 | 5:56 | 8:40 |

Based on the manufacturing times for both variants and both ways for choosing cutting conditions obtained from simulation, the conclusion is that the variant 1 with the adopted cutting conditions from the tool catalogue Sandvik Coromant represents a more suitable option.

## 4. CONCLUSION

The main purpose of technological preparation of production is to provide successful process planning while considering a large number of variants in the shortest possible time.

One of the main problems in process planning is the fact that multi-dimensional planning tasks are defined in a linear form which is particularly important for defining sequences of machining and process operations. In this way, an obtained solution is very far from the optimal one. A number of variants of process plans from the given aspect mostly depend on the availability of machines and fixtures, types of alternative operations for machining each feature, a number of alternative tools for performing machining operations and a number of alternative tool approach directions. Similarly, these variants can also be significant in terms of selecting cutting conditions and machining strategies, applying cooling and lubricating assets and so on.

In this paper, process planning in based on a modern approach that is concerned with the application of feature technologies, definition of machining operations and determination of required information about available machines, tools, fixtures, cutting parameters etc. According to this, the problem of defining feasible operation sequences using precedence relationships is considered in this paper. Also, the focus was on the optimization of obtained feasible sequences using the simulation technique and adopting the manufacturing time as an objective function. Precedence relationships are defined on the basis of dimensional, geometric, technological and economical precedences by analyzing design and technological characteristics of a shaft that is used as a sample part. Based on these rules, precedence matrices for determining operation sequences are formed, and then these machining operations are grouped into appropriate machining processes, or process operations and the rational variants of process plans obtained at the output. The search process is performed in the Catia software system by simulating machining process for the given variants of process plans.

The defined precedence and time matrices represent the foundation for the optimization of process planning by one of the numerous metaheuristics that provide favorable solutions for complex optimization problems and which would represent a suitable continuation of this research. Likewise, a wide range of alternative machining operations, tools, then machining strategies and cutting conditions can also be considered as the adequate elements for process planning optimization.

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