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Planning optimised multi-tasking operations under the capability for parallel machining

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Abstract: The advent of advanced multi-tasking machines (MTMs) in the metalworking industry has provided the opportunity for more efficient parallel machining as compared to traditional sequential processing. It entailed the need for developing appropriate reasoning schemes for efficient process planning to take advantage of machining capabilities inherent in these machines. This paper addresses an adequate methodical approach for a non-linear process planning with a variety of alternatives, enabled through the STEP_NC standard. A relevant algorithmic approach of high efficacy is developed for feature clustering and operation sequencing based on AND-OR graph modelling. It involves a discrete modelling scheme for setup formulation so that the workload of machine spindles is levelled and its total cycle time is minimized. The so-formulated optimization problem, and related in particular to feature distribution among setups, can be successfully solved by a non-linear generalized reduced gradient (GRC) algorithm. The solution algorithms outlined can be relatively readily implemented in industrial informatics systems of small and medium-sized manufacturing enterprises. The entire methodical approach is validated through an illustrative case study based on an exemplary mill-turn part.

Keywords: CAPP, generic setup, machine assignment, machining feature, process selection and sequencing, reasoning scheme

Nomenclature

F_i	feature *i*
$f_{i,j}$	entry of a FPM for a work part, $i \leq m$, $j \leq$ n, where m –maximum number of required features preceding the specific feature *j*

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F_i (-z)	feature *i* machined from –Z direction; while F_i (+z) – machined from +Z direction
FPM	Feature Precedence Matrix
GMP	Good Manufacturing Practice
GRG	generalised reduced gradient method
J_i	total number of working steps (features) to be realised in setup *i*
L(i)	loading of a part onto a spindle *i*, $i \in \{1, 2\}$
M(1)	machining time for part setups upon the main spindle
M(2)	machining time for part setup upon the sub-spindle
MILP	Mixed Integer Linear Programming
MTM	multi-tasking machine
n_{su}	total number of part setups
OFSM	one-feature simultaneous machining
PAT	Process Alternative Table
PEM	performance evaluation metric
q	production quantity (a batch size)
R_c	operation cycle rate
R_p	hourly production rate
S_{+z}	subset of *m*-features to be machined in a sub-spindle (available for machining from +Z direction)
S_{-z}	subset of *m*-features to be machined in a main spindle (available for machining from -Z direction)
$S_{-/+z}$	subset of *m*-features machinable from both -z and +z directions, i.e. $S_{-z} \cap S_{+z}$
T	working tool
T(R)	machining kinematics with a driven tool (cutting speed v_c attributed to a tool))
TAD	Tool Access Direction (a working direction)
T_c	estimated machine operation cycle time
TFSM	two-feature simultaneous machining
$t_{j,i}$	estimated machining times of feature *j* in setup *i* , $i \in \{1, 2\}$,
t_{sq} (WS_j)	processing time of a WS_j, in sequential mode, where *j* - index of setup-free (residual) features (equivalently to working steps WSs), *j*=1, 2, … , *J; J* - total number of setup-free features, included in the revised $S_{-/+z}$ set
T_{mc}	machine changeover time
$T_{su\,(i)}$	total machining time of setup *i*
$\Delta t_{I\text{-}ub}$	initial workload unbalance
$\Delta t_{ub(sm)}$	unbalance between setups considering the possibility for simultaneous processing of selected features by TFSM mode
$\Delta t_{ub(sq)}$	unbalance between setups for sequential machining mode (without considering the possibility for simultaneous processing of specific features)

uL(i)	unloading time of a part onto a spindle i, $i \in \{1, 2\}$
v_c	cutting speed
WP	work part
WP(*R*)	machining kinematics with work part rotation (cutting speed v_c attributed to a work part)
WS$_j$	working step *j*
x_j , x_{j+J}	decision variables denoting the allocation of feature *j* to a setup (the spindle); $x_j, x_{j+J} \in \{0,1\}$
$\cap$	intersection of two sets
$\setminus$	difference of two sets
$\succ$	precedence relationships among pairs of objects (*m*-features)
$\Rightarrow$	implication logic symbol
$\wedge$	logical conjunction
$\veebar$	exclusive disjunction (XOR) logic symbol
$\sim$	negation logic symbol
$\equiv$	equivalence logic symbol
$\forall$	universal quantification
$\exists$	existential quantification

1. Introduction

Up-to-date manufacturing is realised in a dynamically changing environment by an increased demand for the development of customised, high quality products in reduced time cycles [1], [2]. In previous decades, scheduling strategies were mainly focused on machine tools used in parallel to obtain adequate capacity of the entire manufacturing system of various configurations, such as: dedicated machining lines (DML) or flexible manufacturing systems (FMS). The machine with the lowest workflow was used to be selected for assignment of a new job from the list of unfinished jobs. The bottlenecks occurred in a manufacturing system can be eliminated by workflow balancing in order to maximise the utilisation of machines and/or to maximise the expected production rate [3]. The analogous problem of balancing, aimed at the optimal throughput of mixed-model assembly lines with parallel stations, was reported in [4]. The optimal layout design issues of machining lines comprising a series of multi-spindle workstations, and arranged in sequence, was studied in [5]. These authors proposed a heuristic procedure based on decomposition of the whole set of operations into several subsets to minimise the number of workstations and working spindles as well as the occupied area for the considered line layout.

The introduction of new technologies and innovations has made a new generation of machine tools termed as multitasking machining systems, more responsive to the challenges of the global market. Machines of complex configurations equipped with multiple-spindles and turrets have been developed by the metalworking industry and widely introduced to production plants. Multitasking machines (MTMs) are getting ground nowadays as the resources used in manufacturing complex mill-turn part components [6]. Configuration of complex machine tools may relax some operational constraints in process planning [7]. Another advantage of integrating multiple spindles and tool systems in one production unit is the efficient use of space in terms of footprint to work-space ratio. However, as the number of spindles increases, the working space does not increase proportionally to it, and the size of parts is one of the key factors in determining the number of spindles of a MTM system [8].

The proper utilisation of the machining components of high processing capabilities is a key issue for increasing the production efficiency [9]. Increased adaptability can be achieved by Cloud-DPP assuming a two-layer distributed adaptive process planning based on function-block technology and cloud concept. This methodology supports manufacturing parts with a combination of milling and turning features, and process planning for MTMs to minimize the number of setups and tool changes [10]. Multiple spindles can reduce the number of necessary machining steps to one setup consisting of all operations required for complete machining of a part, without the need for inter-machine part transfers as it takes place in machining lines and FMSs [8]. Multiple turrets reduce the machining time by performing different operations using each of the turrets on a part loaded on one of spindles, or on different parts loaded on different spindles.

The extended range of machining features (*m*-features) can be produced involving different processes, such as: turning, milling and laser hardening [1, 11, 12]. A typical multiple complex machine tool equipped with two spindles and two turrets allows for parallel machining of two workpieces attached to the main- and sub-spindles. Generally, the output of a single machine can be doubled by a twin-spindle machine but an optimal process plan for a parallel processing should be found to reach this aim by achieving the minimum time unbalance of spindle workloads. One-feature or two-feature simultaneous machining employs both turrets to a single spindle. This may lead to further reduction of a cycle time depending on the part design as well as product and manufacturing information (PMI) contained in CAD models and STEP data exchange files [13], [14]. Typically a multi-surface part requiring multiple setups is a good candidate for multitasking machining

[8], [15]. Savings in setup time by simultaneous machining are also effectively realised on mill-turn machine tools with a single spindle and two turrets [16].

Despite more than two decades of intense research and remarkable progress, there is still a considerable need for further research in many aspects of automated process planning. Therein, computer aided process planning (CAPP) is considered as the key technology for the integration of computer-aided design (CAD) and computer aided process manufacturing (CAM) in production area [17]. Chung and Suh [1] developed an optimisation algorithm based on STEP-NC and graph modelling minimising the total cycle time, employing the branch-and-bound method and heuristics from engineering insights. The investigation of feature-based toolpath generation with a prediction of surface quality was proposed in [12]. The manufacturing knowledge contained in STEP-NC was utilised for generic process planning and especially for the turning process optimisation [18].

The automatic process planning systems based on *m*-features recognition for complex parts to be produced on technologically advanced machine tools were developed in [19, 20]. Their authors pointed out the advantages of the application of two-turrets machines as well as the importance of the workload unbalance for turrets. Dolgui et al. [5] in turn developed efficient heuristic algorithm for multi-station machining lines performing even several dozen operations. It was based on an improved Mixed Integer Linear Programming (MILP) model and a new heuristic of its decomposition to achieve the best line-balancing. Tolerance based approaches for automatic reasoning for defining operations for prismatic and mill-turn parts were presented in [21, 22]. It assumed a heavy reliance on a data input model incorporating functional requirements for parts and in particular GD&T references. The analysis of parallel processing capability of a manufacturing flexible cell with a set of machines equipped with multiple spindles and turrets was performed in [11, 23]. The scheduling problem was formulated also as a MILP model. A genetic algorithm, simulated annealing, iterated local search, iterated greedy algorithms as well as artificial immune algorithms were applied to searching for the best result.

Su Y. et al. [24] focused on process planning optimisation on a multi-spindle and a multi-turret turning machine tool. The operations were scheduled with multiple objective, such as: minimising machining cost and maximising the machine utilisation. The optimal process plans were generated by a hybrid genetic algorithm based on a mixed 0-1 integer programming model

A two-tier system architecture has been adopted in this research (Fig. 1) to enable the desirable adaptive CAPP, as explicitly advocated in some recently encountered reports, e.g. [2, 25, 26, 27]. The role of the supervisory tier (upper level) of the CAPP system is meant two-fold, and namely as: generic (machine – neutral) process planning in the units of work setups, which are clusters of interrelated *m*-features - designated based on attached attributes, and then establishing their appropriate sequence. It is worth mentioning therein that feature–based CAPP planning by part setups is recognised as prospective in the face of the progressive digitisation of manufacturing processes in the era of Industry 4.0 and the Internet of Things [9]. The lower tier of the decisional system in turn is meant to enable detailed process specification with alternative solutions, assuming the possibility for finding optimised setup designs on a definite machine, considering its actual operational capabilities. The latter facility is, in particular, feasible owing to currently accessible the STEP-NC standard whose data model is formalised as ISO 14649 STEP [28], and which in essence allows for conditional selection (with the use of conditional clauses for non-linear process development) of many alternative process plans in terms of the working step sequence for machining the features while part fabrication [11, 18, 29].

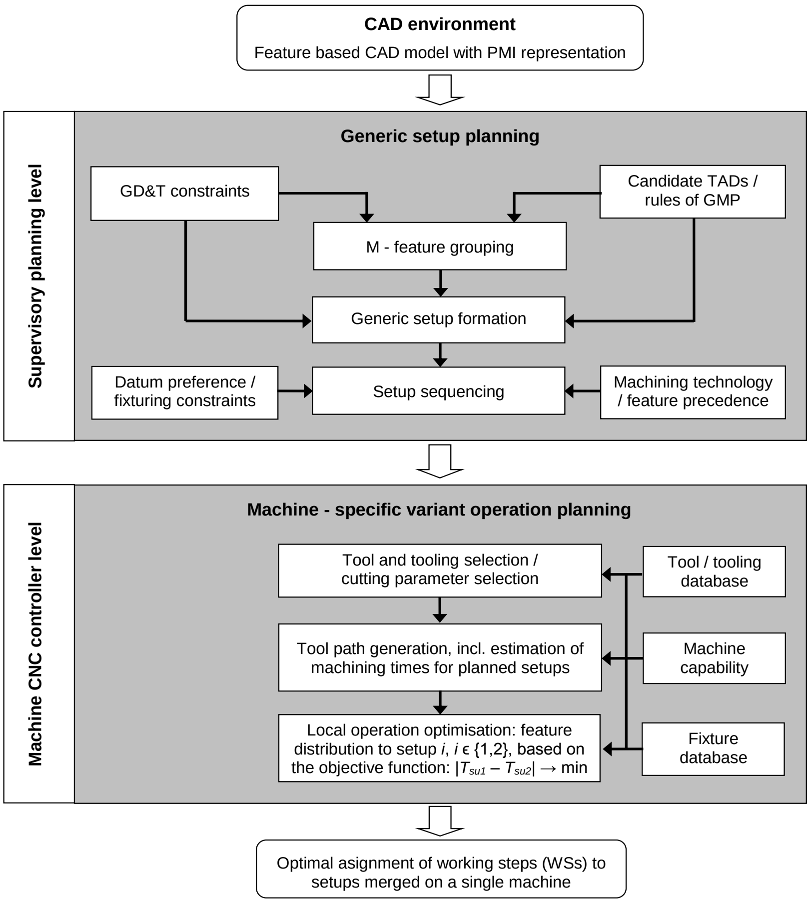


Fig. 1. Overall structure of optimal process planning for mill-turn parts with parallel processing capabilities

Considering the above, the efficacious algorithm for optimised setup planning and operation sequencing in MTMs with the capability of parallel machining is proposed in this research paper. A relevant algorithmic approach that can be successfully implemented in industrial informatics systems is outlined for machining feature clustering and operation sequencing so that the machine utilization level is increased and its total cycle time minimised. The proposed approach is validated through a sample workpiece consisting of both turning and milling features. The model of spindle balancing is formulated as the 0-1 discrete non-linear programming problem.

2. Chief Aspects of Multitasking Machining

There are definite significant peculiarities concerning planning processes for multitasking machines, equipped with multiple spindles and turrets for both turning and milling operations. A first one is that those machines offer an extended possibility for implementing the concept of complete parts machining within the working space of a single station. A next peculiarity is associated with the capability for non-linear process planning, with a number of alternative process plans in terms of workingstep sequence, setups based on the use of available spindles, cutting tools sets in operating turrets, and the machining mode used for executing each workingstep, involving also the possible schemes of simultaneous feature machining.

The performance metric normally chosen for envisaged optimisation task is closely linked to the machine cycle time [1]. In a multi-tasking machine (MTM) where more than one part might be machined at the same time with more than one spindle, it is not obvious how to define the cycle time. The focus of this paper is on a MTM machine equipped with two spindles and two independent tool turrets (Fig. 2) since it inherently has the basic configuration of other machines of this category. For this machine, a definite operational scenario can be accomplished, as depicted in Fig. 3. Such an action scenario can be regarded as generic and applicable to all types of multi-spindle machines. The scenario outlined in Fig. 3 involves machining operations of two consecutive parts of a kind, performed in parallel within the setups realised upon the main and sub-spindles as well as the parallel operations for loading a part, shifting it between the spindles and unloading the machine. Easily to note, that especially for the time allocated to the latter activities the machining process cannot be continued, and both spindles remain in idle state. Therein, the cycle time is defined as the total time taken to complete one part component, and means the time elapsing from its loading onto a machine until leaving the machine.

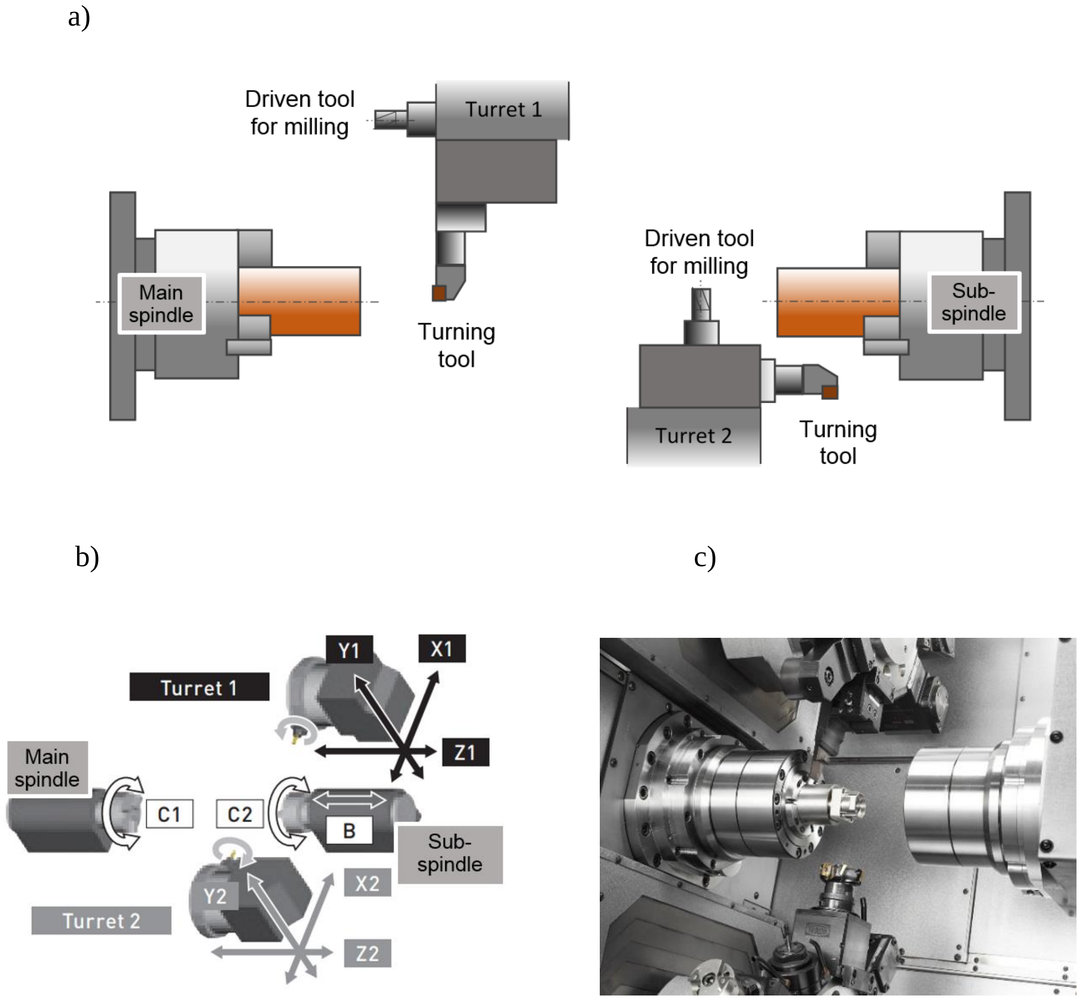


Fig. 2. Analysed configuration of a two-spindle and two turret multi-axis MTM with parallel processing capability (a); the layout of controlled axes of DMG MORI NZX series machines [43] (b); a real example of a TRAUB TNX65 machine [44] (c)

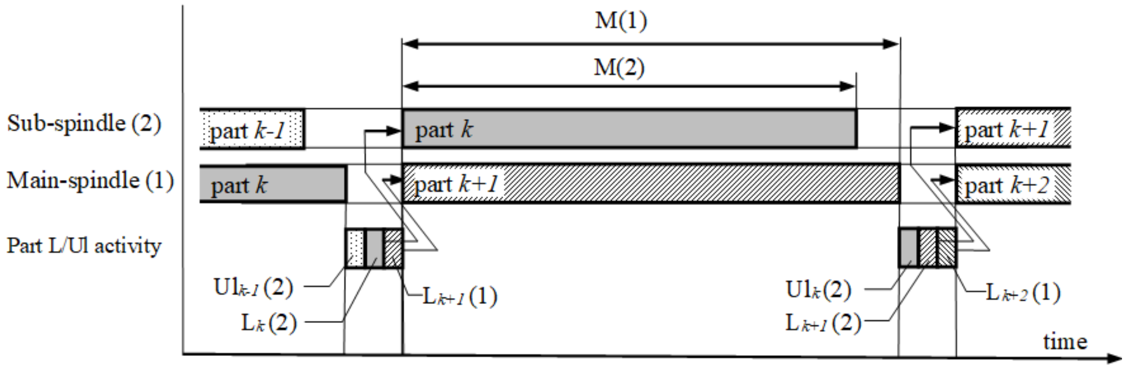


Fig. 3. Gantt chart of the operational scenario on a mill-turn machine with parallel processing capability; L/uL (i) – loading or unloading times of parts onto a spindle i, i ϵ {1,2}, whereas M(1) and M(2) – machining times for part setups upon the main – and sub-spindles, respectively

Assuming large batch sizes (or even mass production conditions), the average hourly production rate R_p [pcs/hr] for the two-spindle MTM equals the operation cycle rate R_c of the machine since the effect of machine changeover time becomes insignificant, viz. $T_{mc}/q \rightarrow 0$ as q (production quantity) becomes very high.

The aforementioned ratio can be determined by the following equation:

$$R_p \rightarrow R_c = \frac{60}{\max\ \{[L\ (1) + L\ (2) + uL\ (2) + M\ (1)],\ [L\ (1) + L\ (2) + uL\ (2) + M\ (2)]\ \}}\ . \tag{1}$$

Closer examination of the equation clearly shows that the production rate is mainly decided by balancing of the two machining times including: the tool change time, tool approach and overtravel times in consecutive working steps, as well as loading -, shifting and unloading times for the part. Since, regardless of the machining case, the latter are significantly smaller than the corresponding machining times and are of constant values; i.e. $L(1) + L(2) + uL(2) \ll M(1)$ *or* $M(2)$, the hourly production rate of the machine can be approximately quantified as:

$$R_p = \frac{60}{\max\ \{M\ (1),\ M\ (2)\}}\ . \tag{2}$$

The equation (2) implies that the production rate is determined by the bottleneck machining time in one of part setups. Hence in effect, maximizing the production rate in complex machining on machines with parallel processing capability can be achieved by workload levelling of machine spindles along with simultaneous minimisation of the machining time for the setup upon a spindle identified as the bottleneck.

In case of other production regimes being envisioned such as the manufacture of a part-mix in small batches, however, the machine changeover time per work unit (T_{mc}/q) is due to be included as a component into average production time per work unit, alongside with machine operation cycle time (viz. in the denominator of the expression 1 and 2, respectively).

In the light of the above, the performance evaluation metric (PEM) relative particularly to high-volume processing conditions, and adopted in this research remains as it follows:

$$PEM = \min \ [\max \ \{M(1), M(2)\}] \quad . \tag{3}$$

Formal notation of the metric is also consistent with a mathematical formulation suggested in e.g. [1].

The analysis of multitasking machining systems operation carried out for this research has assumed a deterministic character of implemented in them processes for in parallel part machining, while allowing for the possibility of simultaneous feature machining. Based on industrial practice and for the sake of simplification, it is assumed however that machining mode change (as e.g.: from ordinary sequential to simultaneous feature processing) is not permitted during a machining cycle. Moreover a realised machining working step is not subjected to pre-emption, i.e. the tool turret assigned to its execution cannot be released for a new processing step until the current working step is completed.

Basically, the estimated machine operation cycle time, defined as the time taken to process one work part, amounts to:

$$T_c = \max \ \{T_{su(i)}\}, \quad i \in \{1, 2\} \tag{4}$$

where $T_{su\,(i)}$ is a total machining time of setup i defined as follows:

$$T_{su(i)} = \sum_{j=1}^{J_i} t_{sq} \, (WS_j) \tag{5}$$

and where $t_{sq}\,(WS_j)$ is the processing time, in sequence mode, of the WS_j working step assigned to setup i, and J_i is the total number of working steps to be realised in this setup.

The use of the mode of simultaneous machining for designated features (assumed in this study chiefly with regard to the main spindle) has a measurable effect on the value of the estimated cycle time and process efficiency. It is the result of the difference in the time gain from overlapping of times for two different WSs performed in the main spindle, and the time loss due to the unavailability of the other turret for another WS (setup), performed in the sub-spindle while both turrets are involved in simultaneous machining. Closer formal explanation of such a machining instance can be found in e.g. [1]. The alternative operational scenarios for a machine cycle with parallel processing capability chart are depicted in the form of Gantt charts in Fig. 4. Mathematical formulation for calculating the time-related workload imbalance between spindles considering the mode of simultaneous machining of *m*-features are given in detail in Section 4.

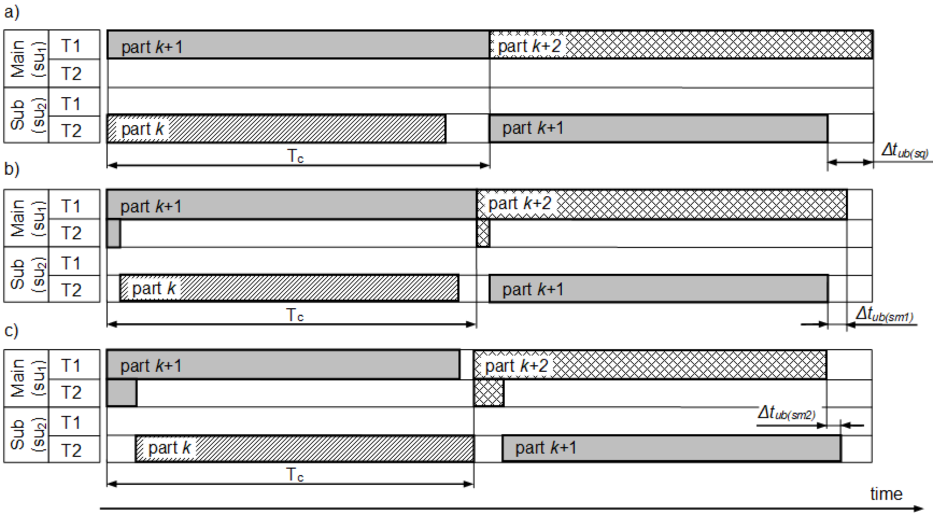


Fig. 4. Gantt chart of the operational scenarios for a machine with parallel processing capability, and consistently with the sequential machining mode of the individual features in setups (a), and under allowing for the possibility of simultaneous feature machining (of different time duration) upon the main spindle (su_1) (b and c); where: T_c – machine operation cycle time, and $\Delta t_{ub(sq)}$, $\Delta t_{ub(sm1)}$ and $\Delta t_{ub(sm2)}$ - the resulting values of the time unbalance for both spindles, respectively

3. Representation of Information Relationships in an Input Data Model

For process planning efficiency reasons, the authors propose an extended feature classification scheme correspondingly to the needs of rational process plan selection for addressed category of part types. The main premise in setup planning and operation sequencing is to determine the accessibility of *m*-features for tools. For mill-turn parts, this applies mainly to the -Z and +Z TADs (working directions), accordingly with the workpiece coordinate system that coincides with the axis of part rotation (the datum axis) as by default assumed in existing literature [2]. This is shown for the sample mill-turn workpiece, consisting of 16 *m*-features of definite technological requirements – Fig. 5.

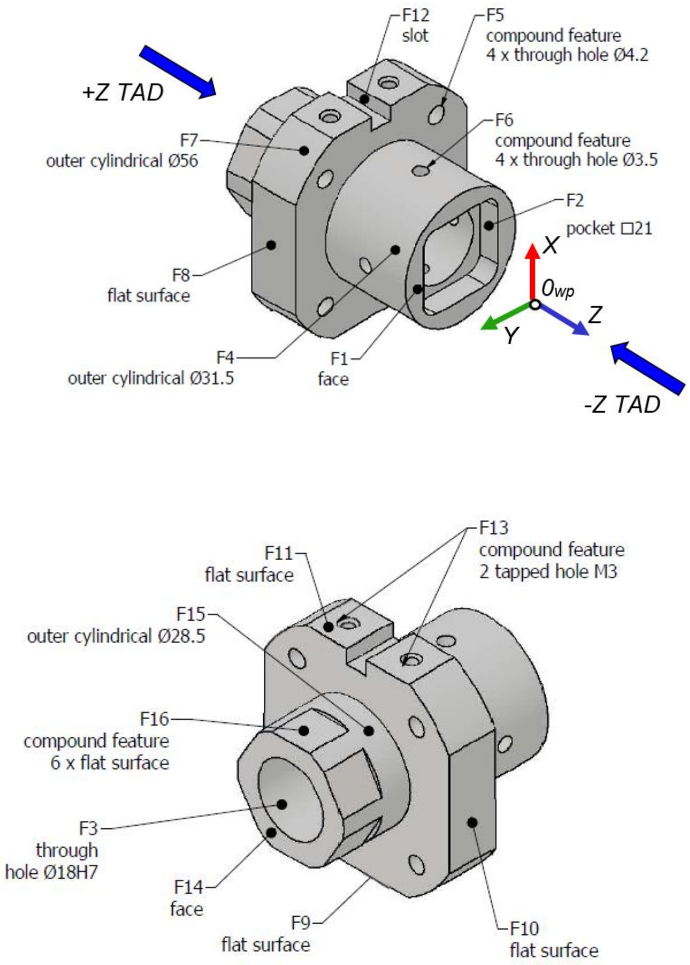


Fig. 5. A sample work part used in an illustrative case study with the specification of present machining features F_i and selected geometrical requirements

For the sample work part and for a mill-turn centre with four controlled axes $\{x, y, z, c\}$ and typical processing capabilities, the sets of features to be machined in a main spindle (S_{-z}) or/and in a sub-spindle (S_{+z}) are as follows:

$$S_{-z} = \{F_1, F_2, F_3, F_4, F_5, F_6, F_7, F_8, F_9, F_{10}, F_{11}, F_{12}, F_{13},\} \tag{6}$$

$$S_{+z} = \{F_3, F_5, F_7, F_8, F_9, F_{10}, F_{11}, F_{12}, F_{13}, F_{14}, F_{15}, F_{16}\}. \tag{7}$$

Thereby, the *m*-features presented in both sets, i.e. those belonging to the intersection of $S_{-z} \cap S_{+z}$, termed further as a $S_{-/+z}$ set, might be processed from either -Z or +Z direction. The intersection of the above given sets S_{-z} and S_{+z} is given as:

$$S_{-/+z} = \{F_3, F_5, F_7, F_8, F_9, F_{10}, F_{11}, F_{12}, F_{13}\}. \tag{8}$$

Since, as a matter of fact, the objective is concerned with minimising the total number of setups, the focus be on merging those features into the subgroups of the setup-dependant features, and available for machining exclusively from either -Z or +Z direction. The initial subgroups of the setup-dependant features are determined as the difference of sets $S_{-z} \setminus S_{-/+z}$, and the difference of sets $S_{+z} \setminus S_{-/+z}$, termed further as S_{i-z} and S_{i+z} set, respectively. For the given sets S_{-z} and S_{+z}, the initial subgroups of the setup-dependent features processed from the specified -Z or +Z direction are given as:

$$S_{i-z} = \{F_1, F_2, F_4, F_6\} \tag{9}$$

$$S_{i+z} = \{F_{14}, F_{15}, F_{16}\}. \tag{10}$$

Summing up, features F_1, F_2, F_4 and F_6 can be machined only from –*Z* direction, and the features F_{14}, F_{15} and F_{16} only from +*Z* direction, while the rest of features from both directions.

4. Algorithmic Approach for Optimised Setup Forming and Process Sequencing in Multi-Tasking Machining

A concept of system structure capable of non-linear process planning, enabled by the STEP_NC standard [30], and whose data model is formalised as ISO 14649 [1], is assumed in this paper. This entails finding an optimal solution for a process sequence in terms of time, among those many possible alternatives, which are available in case of complex multi-tasking machining. Because of the time aspect, the problem tackled in this research can be viewed as a combinatorial optimisation task combining process sequencing and predictive scheduling [31]. Basics of a set theory and graph modelling, interchangeably with the corresponding matrices of relationships are therefore applied to the formalisation of the developed algorithmic procedure to make most of the extended capability for planning with process alternatives, feasible in multi spindle MTM machines [32]. Following the assumptions and findings given above, the adequate solution algorithm for setup planning and operation sequencing in complex multi-tasking machining systems envisioned, is summarized in Table 1.

Table 1. Solution algorithm for optimised setup planning and operation sequencing in multitasking machines with the capability of parallel machining

Step #	
1	Input of the initial information: (i) define a part related coordinate system and relevant *T*ADs; (ii) identify the dominant rotational-axis to determine the axisymmetric "as-lathed" part model; (iii) designate the reference datums for a part and their dependency hierarchy to determine its location in consecutive setups.
2	List the *m*-features of a work part according to STEP standard along with the specification of their attributes, incl. TADs (working directions), feature location in a work part model
3	Cluster features identified in a work part model into the disjoint sets based on the dedicated attributes, denoted as: S_{-z} and S_{+z} – grouping features machinable from –Z or +Z TADs, respectively – intended for machining in consecutive part setups, and in addition the $S_{-/+z}$ set of features machinable from both these directions; continue by setting out the precedence relationships between the distinguished features, found in the same or different clusters by means of a graph modelling (FPG graph) and the corresponding FPM matrix.
4	Update, if needed, the composition of the set $S_{-/z}$ of residual features by possible re-allocation of selected features to the other clusters (S_{-z} or S_{+z}) re-considering the existing feature precedence constraints, due to the rules of good manufacturing practice (GMP) and the criterion for minimizing the number of part setups.
5	Assign the residual *m*-features of the updated $S_{-/+z}$ set (termed further as the setup-free features) to setups using 0-1 non-linear optimisation method, with the objective function aimed at minimising the time unbalance between the setups, performed by the sequential machining mode, and termed as: min $\lvert \Delta t_{ub(sq)} \rvert$= min $\lvert T_{su1} - T_{su2} \rvert$.

	6	Verify the possibility for simultaneous processing some features within specific setups for improved process layout and, if any, then calculate the resultant value of workload unbalance between spindles, as: $\Delta t_{ub(sm)}$.

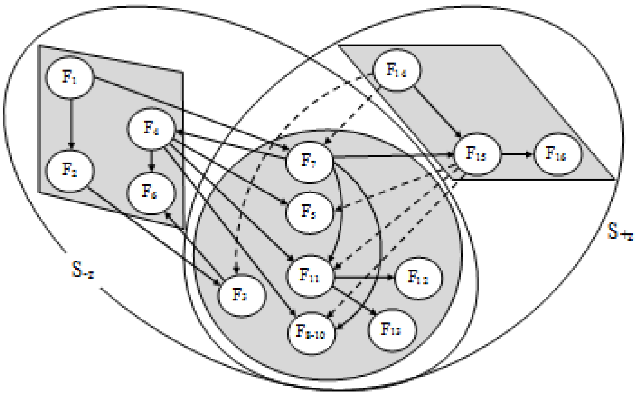
As seen, the developed procedure is realised sequentially in several steps, whereas its two initial steps are related to the retrieval and formal compilation of the data required under the input information model. The activities performed at this preliminary stage of the decision procedure (step 1 and 2) embrace: (i) designating the order of the reference (datum) feature(s) (incl. the primary – , secondary datum surfaces, etc.) for a work part, and correspondingly, the datum dependency hierarchy by the appropriate datum reference frame (DRF) [33, 34], determining the adequate placement(s) of the work part in the working space of a machine tool [2], (ii) identifying the dominant rotational-axis in order to generate the so called axisymmetric "as-lathed" component of a part model, as suggested in e.g. [21]. These starting arrangements, made with limited involvement of a human process planner, are followed by STEP-compliant specification of *m*-features of a work part together with their respective attributes (as e.g. in the modelling based on the enriched *m*-features, introduced by Wang et al, 2006 [26]). As previously also suggested by the authors [2], these attributes referred to, concerned in particular the TADs for features and their location in a work part model, defined in the coordinate system assigned to it. The subsequent step (step 3) of the procedure is concerned with splitting the extracted features into three disjoint sets of features, denoted as S_{-z}, S_{+z} and $S_{-/+z}$, based on the determined attribute. The first two of these include *m*-features accessible for a tool working from –Z or +Z direction respectively, termed further as setup-dependent features and intended for processing in consecutive setups su_1 and su_2. The latter set in turn involves those features which can be machined from any of .those available TADs. Milling and drilling features nested in other features of the "as-lathed" axis-symmetric part model are in particular given the working direction (TAD) consistent with that attributed to the turning feature. Further on, in the same step, this categorisation of *m*-features is completed with the formalisation of existing feature precedence relationships by the FPG graph and the corresponding FPM matrix (see the section below), with reference to those found within a cluster (the interior relationships) and also those in various clusters (exterior interrelations). With regard to the latter activity, a variety of operation sequencing principles, widely reported in related literature, are applicable. It involves various approaches based on the notion of the readiness of a feature for machining [2, 35] or the reasoning rules associated with the understanding the term of actual machining volume AMV [26] as well as those categorised by Mokhtar & Xu, 2011 [29], as compilations of hard precedence constraints (HPC) or soft precedence constraints (SPC), to mention just a few. The following step 4 of the decision algorithm assumes updating the sets of setup-dependent features, appropriated for machining in the main – and the sub-spindle. This updating activity is realised by re-consideration of existing feature precedence constraints in the FPG graph, as a part of the decision scheme. The rationale behind this is the pursuit of reducing (minimising) the total number of part setups in the machining process ($n_{su} \rightarrow \min$), consistently with GMP rules. In this regard, the number of setups should be generally in line with the number of spindles available in the machine used. This is of importance in case of the occurrence the precedence constraints between features originally assigned to $S_{-/z}$ and those present in S_{-z} or S_{+z}.

The detailed reasoning procedure for re-allocation of selected features to the other clusters is described in the following section 4.1. An appropriate model for optimised operation sequencing in multi-spindle machining of mill-turn parts is developed in section 4.2. The final component of the proposed decisional procedure is the planning activity of the step 6, and concerning the possibility for incorporating the simultaneous machining modes into the generated process plan alternatives. This issue is tackled in detail in section 4.3. The essence of the decision scheme is further illustrated through the instance case application, discussed in Section 5.

4.1 Inference Schema on Feature Assignment to Generated Setups

The initial input information model is primarily represented by the directed feature precedence graph (FPG) and the precedence matrix FPM, accordingly with the proposal reported in [35] and [36]. These visualisation models can be readily generated in an interactive fashion by a process planner, based on part design data. Thus, the adequate graph and related FPM matrix, reflecting the feature interactions for the sample part from Fig. 5, and considering the assumed capabilities of machine resources, are shown in Fig 6.

a)



b)

$$\begin{array}{r|cccccccccccccccc}
\text{Feature \#} & F_1 & F_2 & F_3 & F_4 & F_5 & F_6 & F_7 & F_8 & F_9 & F_{10} & F_{11} & F_{12} & F_{13} & F_{14} & F_{15} & F_{16} \\
\hline
 & 0 & 1 & 2 & 7 & 4 & 3 & 1 & 4 & 4 & 4 & 4 & 11 & 11 & 0 & 7 & 15 \\
\mathbf{FPM} = & -1 & -1 & 14^{*} & -1 & 15^{*} & 4 & 14^{*} & 7 & 7 & 7 & 7 & -1 & -1 & -1 & 14 & -1 \\
 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & 15^{*} & 15^{*} & 15^{*} & 15^{*} & -1 & -1 & -1 & -1 & -1
\end{array}$$

Fig. 6. Clusters of features to be machined in subsequent part setups along with specification of the corresponding TADs and the precedence relationships (a), and the associated FPM matrix (b), for the sample workpiece utilised in an illustrative case study; $\mathrm{S}_{-/+\mathrm{z}} = \mathrm{S}_{-\mathrm{z}} \cap \mathrm{S}_{+\mathrm{z}}$; $^{*)}$ at some FPM elements and dashed lines on the graph (a) are due to the occurrence of alternative process solutions considering the selection of predominant working direction according to GMP (setup preference)

Those *m*-features that occur in both sets, might be assigned to a specific TAD set, based on a designated reasoning scheme. This applies, in particular, to the feature F_7 which can be machined from either S_{-z} or S_{+z}. Since, in the FPG graph, the feature F_7 is the direct consequent of F_1 (i.e. the edge $t_1=(F_1, F_7)$ is incident out of F_1, which can be machined only from –z TAD), and simultaneously the feature F_7 is the direct predecessor of F_4 (the edge $t_7=(F_7, F_4)$ is incident into F_4 in the FPG graph, which can be also machined from –z) it is by the implication included into S_{-z} set. The reasoning procedure due to be observed feature relationships is represented as follows:

```
if $F_i \in S_{-z} \cap S_{+z}$ and $F_j \prec F_i \prec F_k$
    if $F_j \in S_{-z}$ and $F_k \in S_{-z}$
        $F_i \rightarrow S_{-z}$
    elseif $F_j \in S_{+z}$ and $F_k \in S_{+z}$
```

```
            $F_i \rightarrow S_{+z}$
        else
            run procedure for distribution of relevant features included in $S_{-/+z}$ to $S_{-z}$ or $S_{+z}$
        end
    end
```

As it can be also seen, the F_3 feature is allocated to the set of S_{-z}. based on the same reasoning frame and due to the rigid assignment of F_2 and F_6 into S_{-z} set.

As a result of the above, the *m*-features can be finally assigned to the three disjoint TAD sets as far as the instance case study based on an exemplary part design is concerned (see Fig. 7).

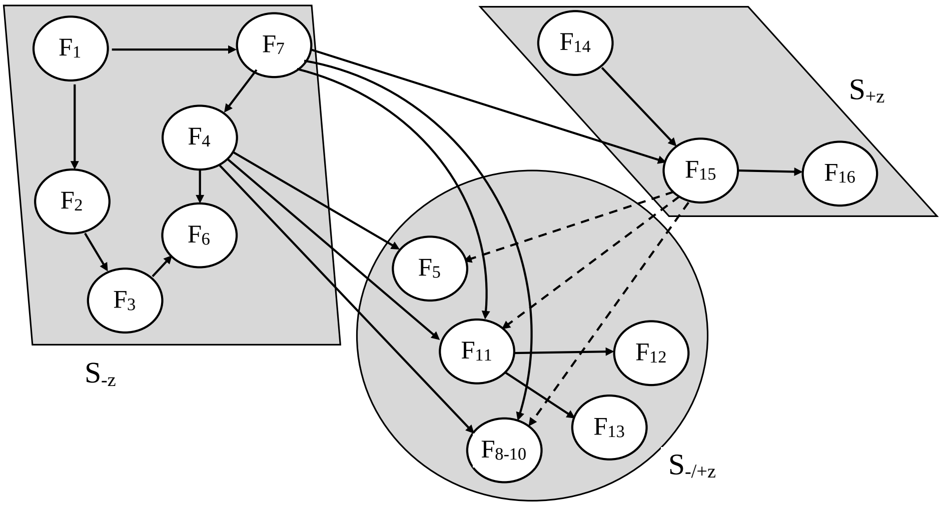


Fig. 7. The updated assignment of features to definite disjoint TAD sets for the work part shown in Fig.5, along with occurring feature precedence interrelations

The feasible alternatives for the assignment of *m*-features to setups formed can be mapped in the form of AND-OR graph (Fig. 8), based on [37]. This modelling scheme covered a two-stage decision making on allocation of both designated categories of *m*-features, i.e. those setup-dependent as well as those setup-free, observing established feature sequences in consecutive setups, as given in Fig. 7. The above mentioned AND-OR graph modelling facility is thereby particularly utilised in representing all valid process realisations, and in particular with the reference to the allocation of *m*-features to generated setups, regardless of a machine tool.

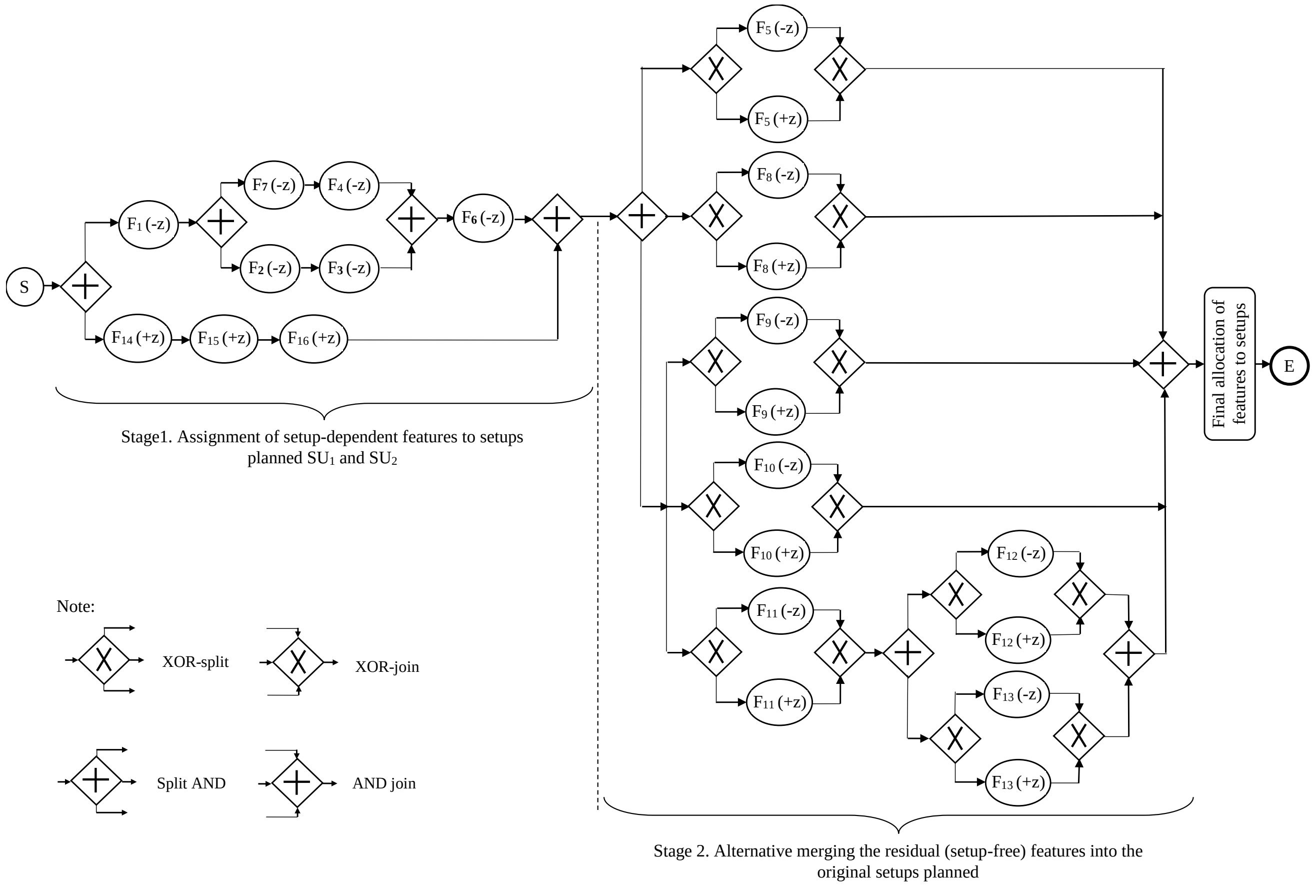


Fig. 8. Mapping the feasible alternatives for allocation of *m*-features to setups in parallel processing of a work part of the case study, based on AND – OR graph modelling

4.2. *Model Formulation for Optimised Operation Sequencing*

Generating the optimised process plan for the analysed machine types boils down to appropriate separation of the setup-free features (termed further as the residual features in the updated $S_{-/+Z}$ set) and their combination with those setup-dependent ones into the setups, accomplished in the main – and sub-spindle, respectively. This is all meant to ensure that the workload for both spindles is levelled, and thus the total machine cycle time is minimised under the constraints due to the configuration of the machine tools and related equipment.

The algorithmic approach proposed for splitting the residual features among preliminary formed setups and consequently leading to levelling workload between the machine spindles is an inseparable part of the decision framework under discussion (see step 5). It is embedded in the 0-1 non-linear optimisation modelling scheme since in the case of the problem classes studied, both the objective function and some of the required linearity conditions usually cannot be met [38]. Moreover, the above mentioned model constituent part is equivalent to the 0-1 multiple-choice resource allocation problem, as categorised in a review paper of Bretthauer & Shetty [39].

In general, solving the related planning task boils itself to finding the minimum of the objective function, assumed as the absolute value of the difference between the machining times of the features performed by setup1 (in main spindle) and by setup2 (in sub spindle), respectively, as it follows:

$$\min z = \min(|\Delta t_{ub(sq)}|) \tag{11}$$

where

$$\Delta t_{ub(sq)} = T_{su1} - T_{su2}. \tag{12}$$

Going further, a mathematical model for solving the optimisation problem undertaken can be formulated as the 0-1 discrete non-linear programming task, with the objective function, given in the following form:

$$\min\ z = \left| \sum_{j=1}^{J} t_{j,1} x_j - \sum_{j=1}^{J} t_{j,2} x_{(j+J)} + \Delta t_{I-ub} \right| \tag{13}$$

where: j – index of setup-free features (equivalently to working steps WSs), j=1, 2, … . J, where J – the total number of residual (setup-free) m-features, included in the revised $S_{-/+z}$ set and subject to the distribution between the spindles; $t_{j,1}$ and $t_{j,2}$ – estimated machining times of feature j in setup1 and setup2, respectively; x_j and x_{j+J} – decision variables denoting the allocation of the features to the individual setups (spindles); Δt_{Iub} – the initial time-related unbalance of spindle workloads, calculated as the difference in the total machining time of su_1 and su_2, considering solely setup-dependent features, incorporated in the updated feature sets S_{-z} and S_{+z}.

Assuming that, $t_{j,1} = t_{j,2} = t_j \quad \forall\ j = 1, 2, \dots, J$ leads to a simplified notation, as follows:

$$\min\ z = \left| \sum_{j=1}^{J} t_j (x_j - x_{(j+J)}) + \Delta t_{I-ub} \right| \tag{14}$$

The decision variables in the above given objective function subject to:

$$x_j, x_{j+J} \in \{0,1\} \quad for \quad j = 1, 2, \dots, J \tag{15}$$

wherein the x_j denotes the assignment of the j-feature to the main spindle (su_1) or lack thereof, whereas x_{j+J} stands for its assignment to the sub-spindle (su_2) or the lack thereof, respectively.

The necessary constraints in the model formulation can be formally defined, as:

(i) $$\sum_{j=1}^{2J} x_j = J \tag{16}$$

that is equivalent to the assignment of all the residual (setup-free) features to the realised setups;

(ii) $$x_j + x_{(j+J)} = 1, \quad \forall\ j = 1, 2, \dots, J \tag{17}$$

added to, as a result of modelling the condition: $\sim(x_j = 1 \wedge x_{(j+J)} = 1) \equiv (x_j = 0 \veebar x_{(j+J)} = 0)$, and which in essence means the assignment of a residual feature to solely one of the two setups;

(iii) $$x_q \le x_p,\ \forall\ F_p, F_q \in S_{-/+Z}\text{, with } F_p \succ F_q \text{ and } p, q \le J\ (p \ne q), \tag{18}$$

where: $S_{-/+z}$ is the subset of the residual features.

The latter constraint constitutes a restriction established in order to model the implication: $x_q = 1 \Rightarrow x_p = 1$, which is due to reflect the existing interior precedence relationships among pairs of features included in the set $S_{-/+z}$, if any. As a result it allows to maintain the required feature precedence for machining in formulated setups.

As noted with this regard, the generalized reduced gradient (GRG) method could be successfully adopted to solving the decision problem under study. This is in particular due to its capability for accommodating the formulated inequality constraints. Its application with reference to the case studies carried out allows to determine the optimal design solution in significantly shorter time as compared to the alternative application of the evolutionary algorithms.

4.3. Verifying the Possibility for Simultaneous Feature Processing

The reasoning scheme for non-linear process planning envisioned also the machining capability for simultaneous operation of two turrets involved into the part processing. The possibility for realisation of such a machining mode has been focused principally on the TFSM model [1]. Simultaneous machining two various features F_v and F_u in one setup requires the same machining kinematics, i.e. the following exclusive disjunction is to be met: v_c: $WP(R) \veebar v_c$:$T(R)$ which means that the cutting speed - v_c is attributed to either a work part (WP) or the working tool (T) [40]. The feasibility of a simultaneous machining the features, in individual process alternatives found, by the concept of the TFSM model can be effectively realised by checking the following conditions:

(i) $\exists\, F_v \in S_{-z}$ whose entry in the FPM matrix,
$f_{1,v} \neq 0$ *and* $t_{sq}(WS_v) < \Delta t_{ub(sq)}$, (19)

(ii) $\exists\, F_u \in S_{-z}$, with $f_{iu} \neq v$, for $1 < i \leq m$
and $v_c: WP(R) \veebar v_C: T(R)$, for both F_v and F_u. (20)

Where there are however multiple features meeting the above given (ii) condition, as the feature F_u, for simultaneous machining, qualify the one with the longest processing time.

In case when both conditions are met, the value for the calculated workload unbalance is due to be updated, as:

$$\Delta t_{ub(sm)} = \left|\Delta t_{ub(sq)} - 2 * t_{sq}(WS_v)\right|, \tag{21}$$

when

$$t_{sq}(WS_v) \leq t_{sq}(WS_u) \tag{22}$$

or

$$\Delta t_{ub(sm)} = \left|\Delta t_{ub(sq)} - t_{sq}(WS_u) - t_{sq}(WS_v)\right| \tag{23}$$

otherwise.

It should be pointed out thereby that above given relationships remain valid also when considering the possibility of simultaneous part processing in a sub-spindle, i.e., considering the features included in the set S_{+z}.

5. Instance Applications of the proposed Approach

An adequate case study (case #1) based on the sample mill-turn work part of definite technological requirements, as presented yet in Section 3 and Section 4, was introduced in order to further demonstrate the operation of the developed framework. The work related GD&T references are given in Figure 9.

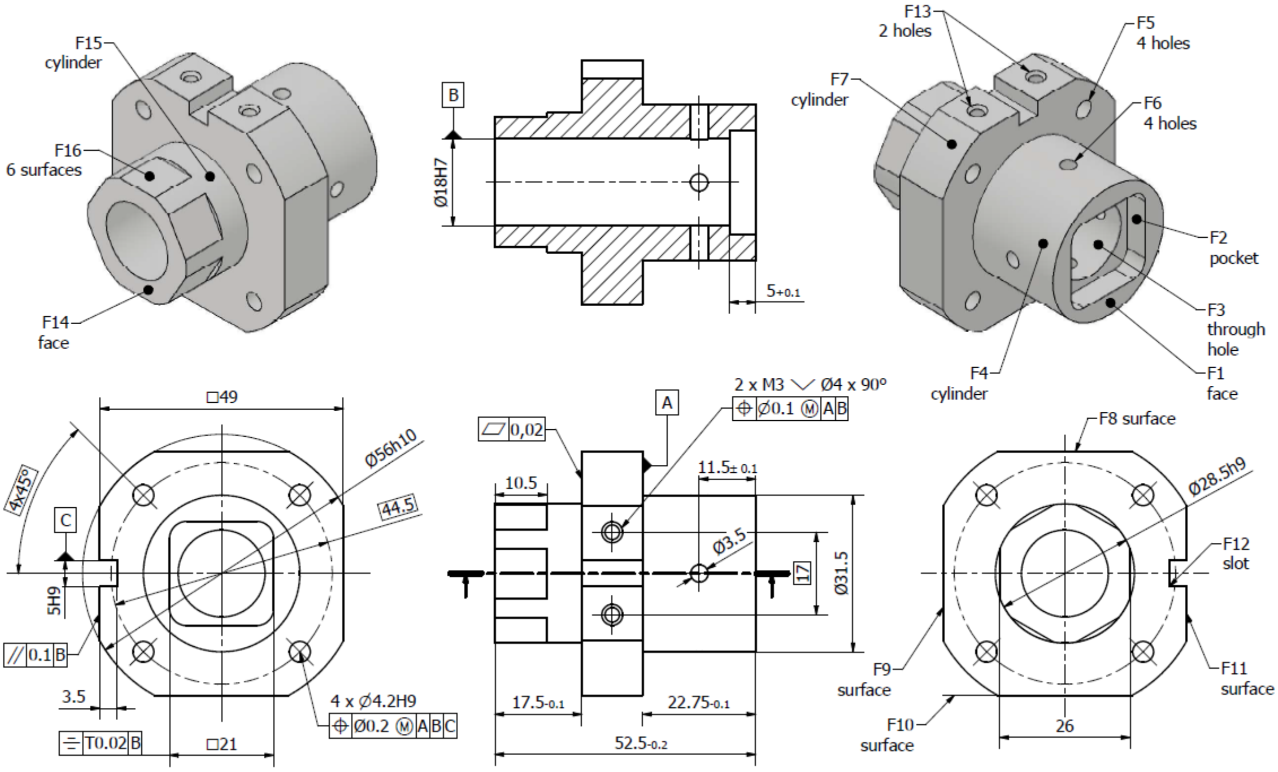


Fig. 9. A sample work part with GD&T data used in an illustrative case #1

Feature precedence graph and related FPM matrix associated with the model component part are depicted in Fig. 6. Fig. 7 shows in turn the status of the part with the updated assignment of features to designated TAD sets generated based on the reasoning schema described in Section 4.1.

A comparative analysis of feasible process alternatives (operation sequences in parallel processing of a work of the instance study) was adequately performed based on the processing times for individual part features, determined at the stage of CNC part programming. Those alternatives are reflected as the AND_OR graph model in Figure 8, while respecting all existing limitations on feature precedence [41, 42], used in detailed model validation.

Thus, an initial unbalance $\Delta t_{I\text{-}ub}$ of 1,20 min was determined under consideration of solely the WSs, related to pre-assigned setup-dependent features, included in the updated sets S_{-z} or S_{+z}, where the former is a set of such *m*-features to be machined solely from –Z direction, including F_1, F_2, F_3, F_7, F_4 and F_6 features and the latter involves the features, machined solely from +Z direction, and namely: F_{14}, F_{15}, F_{16}.

All possible variants for distribution of residual (setup-free) features into generated part setups are specified in Table 2, hereafter referred to as process-alternative table (PAT). The values for the resultant workload unbalance for spindles, included in the last column of this table, were computed based on appropriate processing times for individual WSs, consequently with regard to sequential part machining mode.

Changes in workload unbalance for spindles for permissible variants of the distribution of those identified setup-free *m*-features into setups, and determined in the analysed case study are further visualised in Fig. 10.

Table 2. PAT with various permissible allocation of residual features to setups planned, along with calculated workload unbalance under sequential machining mode

Index	List of setup-free features assigned to setup su_1	List of setup-free features assigned to setup su_2	Computed workload unbalance $\Delta t_{ub(sq)}$ [min]
1	F_5, F_8–F_{10}, F_{11}, F_{12}, F_{13}	none	2.5883
2	F_5, F_8–F_{10}, F_{11}, F_{12}	F_{13}	1.7883
3	F_5, F_8–F_{10}, F_{11}, F_{13}	F_{12}	2.2783
4	F_5, F_8–F_{10}, F_{11}	F_{12}, F_{13}	1.4783
5	F_5, F_8–F_{10}	F_{11}, F_{12}, F_{13}	1.1450
6	F_5, F_{11}	F_8–F_{10}, F_{12}, F_{13}	0.7450
7	F_5	F_8–F_{10}, F_{11}, F_{12}, F_{13}	0.4117
8	F_5, F_{11}, F_{12}, F_{13}	F_8–F_{10}	1.8550
9	F_5, F_{11}, F_{12}	F_8–F_{10}, F_{13}	1.0550
10	F_5, F_{11}, F_{13}	F_8–F_{10}, F_{12}	1.5450
11	F_8–F_{10}, F_{11}, F_{12}, F_{13}	F_5	1.9883

12	F_8–F_{10}, F_{11}, F_{12}	F_5, F_{13}	1.1883
13	F_8–F_{10}, F_{11}, F_{13}	F_5, F_{12}	1.6783
14	F_8–F_{10}, F_{11}	F_5, F_{12}, F_{13}	0.8783
15	F_8–F_{10}	F_5, F_{11}, F_{12} , F_{13}	0.5450
16	F_{11}, F_{12}, F_{13}	F_5 , F_8–F_{10}	1.2550
17	F_{11}, F_{12}	F_5, F_8–F_{10}, F_{13}	0.4550
18	F_{11}, F_{13}	F_5, F_8–F_{10}, F_{12}	0.9450
19	F_{11}	F_5, F_8–F_{10}, F_{12}, F_{13}	**0.1450***
20	none	F_5, F_8–F_{10}, F_{11}, F_{12}, F_{13}	-0.1883
Note: $^{*)}$ minimum value of unbalance between setups for sequential machining mode $\Delta t_{ub(sq)}$ (without considering the possibility for simultaneous processing of specific features)			

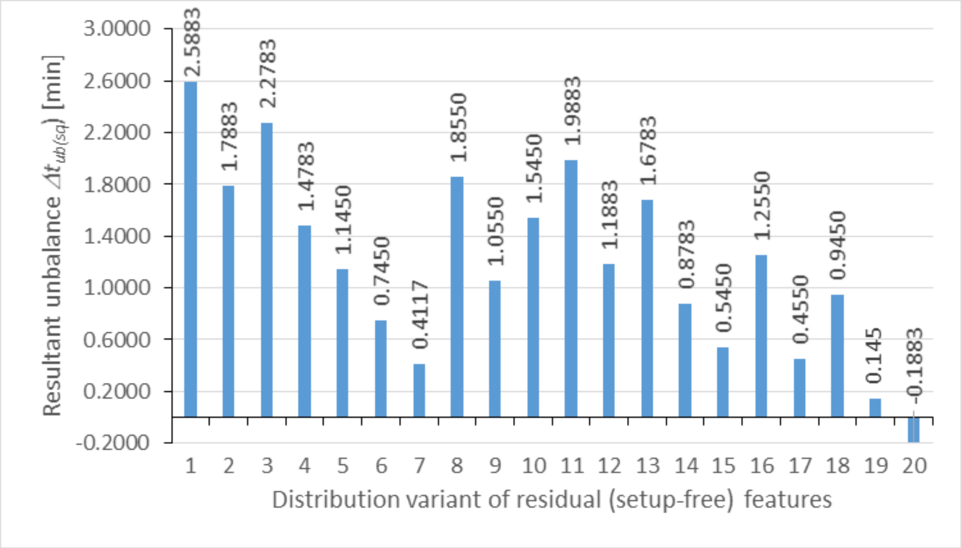


Fig. 10. Time-related workload unbalance of spindles for permissible variants of the distribution of m features into setups under the conditions of sequential machining mode, determined for case #1

The developed algorithm for optimised operation sequencing in parallel machining was run on an Intel(R) Core(TM) i7, based on the discrete-linear programing model formulation presented in Section 4.2. The minimum value of the objective function (time-related workload unbalance) has been computed by the indicated GRG method. It should be emphasized, that the CPU time of the GRG method to determine the optimal design solution (#19 alternative in Table 2) was 0.53 s, and significantly shorter than that of alternatively used evolutionary algorithms, when amounted to 37.56 s. Moreover in further research with additional work part models the trend for exponentially extension of CPU time could be observed with the number of setup-independent *m*-features (part complexity) to be distributed between the setups formed. Due to the same kinematics and after meeting both conditions defined in Section 4.3, a simultaneous machining can be effectively realised for both features F_3 and F_7, as depicted in Fig. 11. As a result, the workload unbalance can be reduced from $\Delta t_{ub(sq)}$ = 0.145 min, as originally determined for sequential machining mode, to $\Delta t_{ub(sm)}$ = 0.0116 min., using the present possibility for simultaneous feature processing.

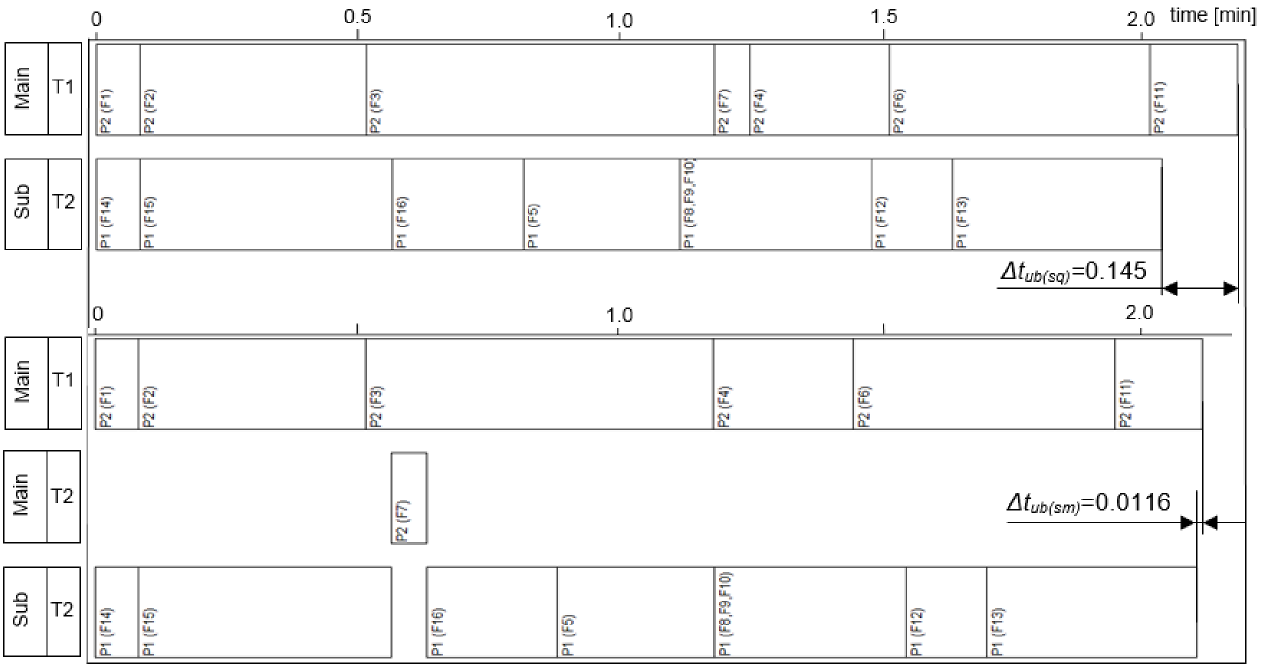


Fig. 11. Operational schedule solutions used in an instance case study: (a) without consideration of feature simultaneous machining in realised setups (a), and with simultaneous machining of features F_3 and F_7 in setup #1, with adequate values of workload unbalance between the spindles, given as $\Delta t_{ub(sq)}$ and $\Delta t_{ub(sm)}$

Reducing the workload unbalance between the spindles resulted in a significant increase in the hourly production rate R_p calculated by Eq. (2). For the process variants related to sequential machining mode with the maximum – (denoted by index #1 in Table 2) and minimum (index #19 in this Table) unbalance value, the values of R_p amounted to 17.62 pcs/hr and 27.48 pcs/hr, respectively. Incorporating a simultaneous machining mode, related to F_3 and F_7 features, yielded the further improvement of the R_p value to 28.35 pcs/hr.

To show the peculiarities of the developed method, two additional case studies derived from the industry have been introduced in extended verification, termed further as case #2 and case #3. Test parts with GD&T references for those cases are presented in Figure 12 and Figure 13, respectively.

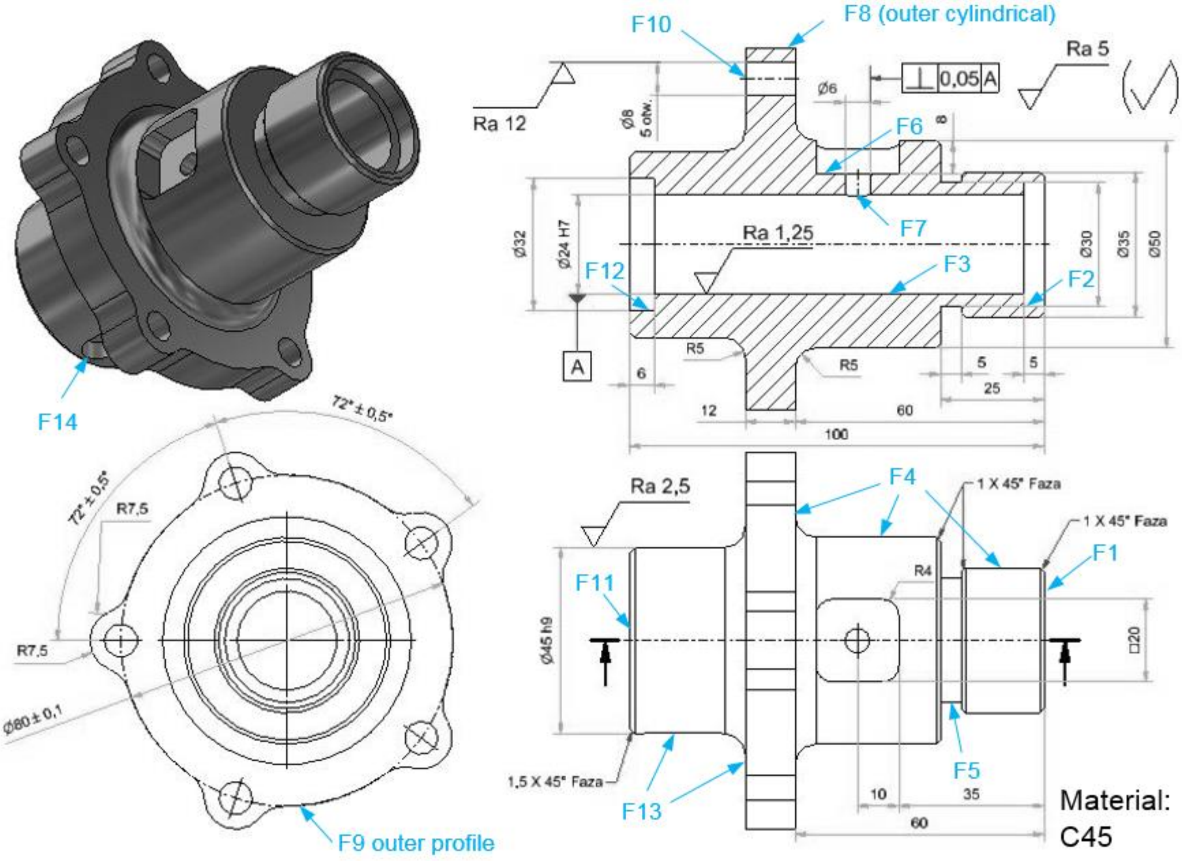


Fig. 12. A test part of case #2 with GD&T data and the specification of machining features F_i

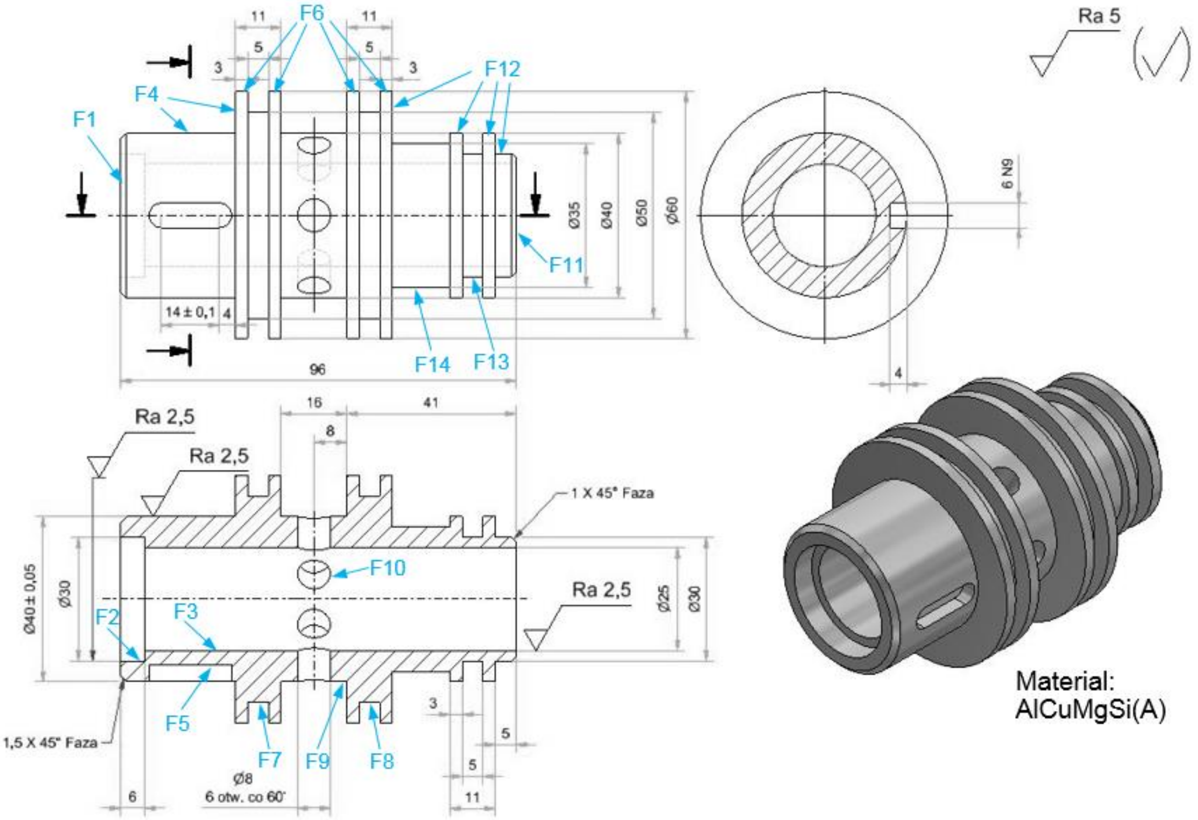


Fig. 13. A test part of case #3 with GD&T data and the specification of machining features F_i

Following the consecutives decision steps of the developed algorithm, the allocation of features to the relevant setup-dependent - and setup-free sets has been accomplished for both cases. Appropriate results are compiled in Table 3 along with determined values of initial unbalance $\Delta t_{I\text{-}ub}$. Next, process alternatives with minimum values $\Delta t_{ub(sq)}$ = -0.1500 min and $\Delta t_{ub(sq)}$ = -0.0333 min of workload unbalance in sequential machining mode were found using a developed procedure, as shown in Table 4 for case #2 and case #3, respectively. Moreover, the possibilities for simultaneous machining of selected features were considered. In the case of the negative $\Delta t_{ub(sq)}$ for sequential machining and according to Equation 21, simultaneous machining on a main spindle leads to increased unbalance which occurred for case #2 while combining machining of the features F_2 and F_4, with $\Delta t_{ub(sm)}$ = -0.3833 min. However, these processing mode was effective for the reduction of the resultant unbalance $\Delta t_{ub(sq)}$ = -0.1500 min to the minimum value of $\Delta t_{ub(sm)}$ = 0.0833 min, when realised in the sub-spindle for the features F_{12} and F_{13}. The efficiency of the proposed method has been verified by the values of the hourly production rates R_p calculated for analysed variants, as shown in Table 4. The reference value of R_p was calculated for the variant with the maximum unbalance value $\Delta t_{ub(sq)}$ = 9.9167 min, and hence with the longest machining time. For the process variants related to sequential machining mode with the maximum and minimum unbalance value, the values of R_p were amounted to 5.20 pcs/hr and 9.02 pcs/hr, respectively. Incorporating a simultaneous machining mode, related to F_{12} and F_{13} features, yielded the further slight improvement of the R_p value to 9.07 pcs/hr.

Table 3. Allocation results of *m*-features to setups planned in analysed cases with calculated initial workload unbalance

Case	List of setup-dependent features for setup su_1*	List of setup-dependent features for setup su_2*	List of setup-free features *	Initial unbalance Δt_{I-ub} [min]
#2	F_1(0.2000); F_2(0.1167); F_4(1.8000); F_5(0.2833); F_8(0.2333)	F_{11}(0.2000); F_{12}(0.1167); F_{13}(1.0000); F_{14}(0.3000)	F_3(1.0833); F_6(2.4500); F_7(0.1000); F_9(5.0333); F_{10}(0.2333)	1.0167
#3	F_1(0.0667); F_2(0.0667); F_4(0.2667); F_5(0.1000); F_6(0.0833)	F_{11}(0.0667); F_{12}(0.3500); F_{13}(0.1000); F_{14}(0.2333)	F_3(0.3833); F_7(0.1000); F_8(0.1000); F_9(0.6333); F_{10}(0.6833)	-0.1667

*) relevant machining operation times in [min], including a tool change time, are given in brackets

Table 4. Allocation of residual features to setups planned for process alternatives with calculated workload unbalance in sequential machining mode and with the inclusion of simultaneous machining

Case	List of setup-free features assigned to setup su_1	List of setup-free features assigned to setup su_2	TFSM included	Resultant unbalance [min]	The hourly production rate R_p [pcs/hr]
#2	F_3, F_6, F_7, F_{10}	F_9	No	$\Delta t_{ub(sq)}$ = -0.1500	9.02
			Yes: F_2 and F_4	$\Delta t_{ub(sm)}$ = -0.3833	8.87
			Yes: F_{12} and F_{13}	$\Delta t_{ub(sm)}$ = **0.0833***	9.07
	F_3, F_6, F_7, F_9, F_{10}	none	No	$\Delta t_{ub(sq)}$ = 9.9167	5.20

#3	F_3, F_9	F_7, F_8, F_{10}	No	$\Delta t_{ub(sq)}$ = **-0.0333**[*]	36.73
	none	F_3, F_7, F_8, F_9, F_{10}	No	$\Delta t_{ub(sq)}$ = -2.0667	22.64
*) optimum values of a resultant unbalance for the analysed cases					

For the case #3 and the process variants related to sequential machining mode with the maximum and minimum unbalance value, the values of R_p amounted to 22.64 pcs/hr and 36.73 pcs/hr, respectively. According to the condition determined by Equation 19, simultaneous machining can be considered only when machining operation times of relevant features are shorter than the minimum unbalance $\Delta t_{ub(sq)}$ determined for the sequential mode. Thus, incorporating a simultaneous machining for case #3 would increase the machining time and lower the R_p value, regardless of the spindle on which it is planned, as machining operation times of all relevant features are longer than the minimum unbalance $\Delta t_{ub(sq)}$ = -0.0333 min – see Table 3 and Table 4.

6. Concluding Remarks

The algorithm for optimised setup planning and operation sequencing in multitasking machines with the capability of parallel machining was developed. Machining features were distributed between clusters considering the existing feature precedence constraints, due to the rules of good manufacturing practice and the criterion for minimizing the number of part setups. The assignment of the residual *m*-features to setups was conducted using 0-1 integer non-linear optimisation method, with the objective function aimed at minimising the time unbalance between the setups. The developed reasoning scheme for non-linear process planning envisioned also the machining capability for simultaneous operation of two turrets involved into the part processing. Developed method allowed to increase the hourly production rate due to minimising the workload unbalance between the spindles for the process variants related to sequential machining mode. The further improvement of the hourly production rate was possible by incorporating a simultaneous machining mode.

Further research is intended towards the extension of the workload balancing method to application instances involving a larger number of tool turrets as well as to cases involving merging setups on collaborating machine resources in flow-type manufacturing systems.

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