Comparative study of 3- and 5-axis CNC centers for free-form machining of difficult-to-cut material

Wojciech Zebala a,1, Malgorzata Plaza b,1,*

a Cracow University of Technology, Faculty of Mechanical Engineering, Aleja Jana Pawła II 37, 31-864 Krakow, Poland
b Ryerson University, TRSM, 350 Victoria St. Toronto, Ontario, Canada M5B 2K3

A R T I C L E   I N F O

Article history:
Received 29 November 2013
Accepted 11 August 2014
Available online 2 September 2014

Keywords:
Free-form machining
Cost modeling

A B S T R A C T

This paper examines the cost effectiveness of 3- versus 5-axis machines for the machining of a turbine blade made of alloy steel EN 34CrNiMo6. The acceptable surface finish cannot be achieved when a free surface is machined on a 3-axis CNC center due to the variation of the tool's position in relation to the part's surface. A feed-rate adjustment algorithm is proposed in this paper as a way to compensate for that limitation. To that end, the following two research questions are addressed: (1) if the algorithm is used, can the required surface finish be achieved on a 3-axis CNC center, and (2) which of two alternatives: a 3-axis (assuming the algorithm is executed) or 5-axis CNC center (without the algorithm) will be more cost effective?

The study demonstrates that if the algorithm is executed, the finish of the surface machined on a 3-axis center reaches a similar standard as can be achieved on a 5-axis center. Additionally, the machining time is reduced by over 17% when compared to the machining time required on the same 3-axis machine when the NC code is not optimized with the feed-rate adjustment algorithm. The cost effectiveness of the two alternatives is compared using the cost model, which is the research contribution and justifies the application of software technology for the machining of complex geometries on a 3-axis machine.

1. Introduction

Machining industry is presented with a growing demand to produce increasingly more complex shapes in harder-to-cut material grades (Gopalakrishnan et al., 2004). A wide variety of options suitable for such tasks are available in the market, but purchasing a machine tool or CAD/CAM technology requires a significant investment and cannot be done without careful consideration. Incorrectly selected technology limits precision, productivity, and flexibility (Arslan et al., 2004), so companies often put more emphasis on performance and technical capabilities than on cost. Due to fierce global competition, cost became as critical as quality when the production process was created (Layer et al., 2002) and research provides evidence that the cost of a machine tool is the most important factor for cost effective machining (Quintana and Ciurana, 2011).

The machining of mechanical parts, such as turbine blades, is challenged with both geometrical complexity and the material's properties. The shape must be modeled as a free-form. Since the blades are exposed to severe conditions, they must be made from special grades of hard-to-cut material, which causes the cutting forces to vary widely (Wei et al., 2011). The risk of a poor surface finish is high because cutting forces strongly influence the surface finish in multiaxis milling of complex geometries (Kovac and Sidjancin, 1997; Bouzakis et al., 2003).

The position of the tool in relation to the machined surface (inclination angle) has a strong impact on the cutting forces (Fontaine et al., 2006, 2007; Daymi et al., 2009). In order to obtain the desired surface finish, the inclination angle must be kept within the predetermined limits (Kline et al., 1982; Li et al., 2004; Baskar et al., 2005; Seguy et al., 2008). On a 3-axis CNC center, the corrections to the tool position are limited, so the angle often falls outside of those limits (Wang et al., 2010). This makes it impossible to achieve the required surface finish (Bouzakis et al., 2003; Fontaine et al., 2007; Lopez de Lacalle et al., 2007). The tool position can easily be corrected on a 5-axis CNC machine, which is more expensive to purchase and maintain, and thus has the higher amortization costs (Quintana and Ciurana, 2011).

The amortization costs can partially be paid off by the benefits of cycle time reduction. Layegh et al. developed a technique in 2012, in which cutting forces are modeled using a mechanistic high level approach and the model coefficients are calibrated from the experimental cuts. The technique allows the cutting forces to be kept constant along the tool path by adjusting the feed-rate, which significantly reduces the machining time for 5-axis machining of...
complex surfaces. The feed-rate adjustments are conducted in NC blocks by an off-line postprocessor that is embedded into commercial CAM software (Layegh et al., 2012).

In this paper, a similar method is proposed. It is called experimental verification (EV) and its objective is to improve the surface finish of complex geometries on a 3-axis machine. EV enhances CAM to compensate for the limitations of a 3-axis machine through the sophisticated application of software. It controls the feed-rate with a greater accuracy than the previous technique, as the cutting forces are calculated by the CAM software from a constitutive thermo-elasto-plastic model using the Finite Elements (FE) method. FE parameters and the model coefficients are calibrated based on the experimental cuts. The calibration is more labor-intensive (Bouzaziz et al., 2006; Qian and Ben-Arieh, 2008; Folgado et al., 2010), making EV more expensive than the previous technique. Therefore, EV will not be used for 5-axis process planning in this study.

The paper addresses the following two research questions: (1) if EV is used on a 3-axis CNC center, can the required surface finish be achieved, and (2) which of the two alternatives: a 3-axis (assuming EV was executed) or 5-axis CNC center (without EV) is more cost effective? The cost model, which is used to compare the cost effectiveness of the two alternatives, is the critical research contribution. The comparison will be conducted for the case study of an extremely demanding application – the machining of a steam turbine blade made of alloy steel EN 34CrNiMo6 (equivalent grade to AISI 4337 or 4130). The alloy was quenched and tempered at approximately 600 °C in order to reach the hardness of 300 Bhn and tensile strength of 1000 MPa. Solid carbide end mills with a ball head shape, which is the recommended tool for 3- and 5-axis free-form cutting applications, were used in this study.

2. Literature review

2.1. Machining of a free-form shape

The surface of mechanical parts such as turbine blades, engine impellers, ship propellers, and injection and die-casting molds, have a complex spatial configuration that must be depicted with the use of free-forms. Since they cannot be described explicitly, free-forms are constructed from a specified set of points or curves. The occurrence of discontinuities and errors in the description of a solid structure cannot be avoided (Budak and Altintas, 1994; Yazar et al., 1994), so free-forms require high-precision manufacturing and extensive utilization of technologies.

Process planning and machining are the two basic phases of free-form manufacturing. The planning phase begins with a model definition process, which is conducted using CAD software. After that, the machining strategy is developed and optimized with the extensive support of CAM technologies (Lu et al., 2005; Roman et al., 2006; Merdol and Altintas, 2008). The paths that can potentially generate the required shape are defined and examined for any possibility of tool interferences during strategy development. If interferences are detected, the tool path is corrected or rejected.

The surface topomorphy depends on the contact condition between the tool and the workpiece (Lopez de Lacalle et al., 2007). In order to assure the specified quality requirement, the cutting forces and wedge temperature must be kept below their critical limits during the machining process (Li et al., 2004; Raksiri and Parichxun, 2004; Ratchev et al., 2006). To ensure this, the chosen tool paths are examined again during strategy optimization. The selected path is optimized and the NC code is generated (Bey et al., 2008; Wan et al., 2008; Zebala et al., 2009).

Turbine blades are exposed to severe conditions and must be made from special grades of hard-to-cut material, such as fireproof steel or other alloys based on nickel and cobalt (Wang et al., 2010). The risks of damaging the workpiece are especially high during the finishing phase due to the significant variation in the allowances left after a rough machining phase. Additionally, the part often has limited stiffness, and since it may also require that longer tools are used to reach into its cavity, severe vibration can be triggered during the machining process (Mamalis et al., 2009; Zebala, 2012), causing surface roughness (Abrari et al., 1998).

The two critical issues encountered during machining are: short tool life, and difficulty to deliver the required surface finish (Mamalis et al., 2009; Zebala and Matras, 2009). Although volumetric capacity is the key criterion for cost optimization (Tansel et al., 2006), the wear of the tool wedge is more significant when hard-to-cut materials are machined (Ozel and Karpat, 2005; Thakur et al., 2009). The optimization of parameters is paramount for the finishing of complex geometries, and research offers solutions that address this issue (Li et al., 2004; Baskar et al., 2005; Peterka et al., 2009). For example, Tunc and Budak (2009) describe an analytical method for identifying the complexity of the process geometry and the continuous variation of tool–work engagement from CAM data (Tunc and Budak, 2009).

One of the critical challenges for strategy optimization is to establish an optimal tool position (Kline et al., 1982; Li et al., 2004; Baskar et al., 2005; Seguy et al., 2008). The angle between the tool and work surface has a direct impact on the length and position of an active cutting edge of an arch-shaped mill, which in turn significantly affects the cutting process. An incorrect tool position

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>tangential cutting force: ( F_{\text{cal}} ) (calculated in CAM), ( F_{\text{abs}} ) (measured during experimental verification) [N]</td>
</tr>
<tr>
<td>R</td>
<td>surface finish parameter (- S_{a} \text{ or } S_{v} \mu m)</td>
</tr>
<tr>
<td>f</td>
<td>feed [mm/edge]</td>
</tr>
<tr>
<td>( a_{p}, a_{e} )</td>
<td>axial and radial depth of cut [mm]</td>
</tr>
<tr>
<td>( v_{c} )</td>
<td>cutting speed [m/min]</td>
</tr>
<tr>
<td>FC</td>
<td>coefficient</td>
</tr>
<tr>
<td>( R_{R0 \text{ Plan}} )</td>
<td>rate of planning phase operator [$/h$]</td>
</tr>
<tr>
<td>( R_{R0 \text{ Mach}} )</td>
<td>rate of machining phase operator [$/h$]</td>
</tr>
<tr>
<td>( R_{R0 \text{ SD}} )</td>
<td>rate of equipment for strategy development [$/h$]</td>
</tr>
<tr>
<td>( R_{R0 \text{ SO}} )</td>
<td>rate of equipment for strategy optimization [$/h$]</td>
</tr>
<tr>
<td>( R_{R0 \text{ EV}} )</td>
<td>rate of CNC center [$/h$]</td>
</tr>
<tr>
<td>( t_{\text{SO}} )</td>
<td>time of strategy development [h]</td>
</tr>
<tr>
<td>( t_{\text{SO}} )</td>
<td>time of strategy optimization [h]</td>
</tr>
<tr>
<td>( t_{\text{EV}} )</td>
<td>time of experimental verification [h]</td>
</tr>
<tr>
<td>( t_{\text{Mach Rough}} )</td>
<td>time of rough machining (two sides of one blade [h])</td>
</tr>
<tr>
<td>( t_{\text{Mach Finish}} )</td>
<td>time of finish machining (two sides of one blade [h])</td>
</tr>
<tr>
<td>( t_{\text{setup}} )</td>
<td>time of set up [h]</td>
</tr>
<tr>
<td>RSC</td>
<td>risk level for damaging the blade or the average quantity of scrap generated during the production [%]</td>
</tr>
<tr>
<td>RM</td>
<td>coefficient</td>
</tr>
<tr>
<td>W</td>
<td>weight of a blank required for one blade [kg]</td>
</tr>
<tr>
<td>NT</td>
<td>number of tools needed to machine one blade</td>
</tr>
<tr>
<td>M</td>
<td>number of blades in one batch</td>
</tr>
<tr>
<td>CT</td>
<td>average cost of one tool [$]</td>
</tr>
<tr>
<td>NT</td>
<td>number of tools required for one blade</td>
</tr>
</tbody>
</table>
may cause a sudden increase in cutting force and/or tool tip temperature above their respective critical values (Antoniadis et al., 2003). The angle can be projected into the cutting plane as two tilt angles, and both must be kept within the range of 5°/20° for optimal machining (Antoniadis et al., 2003; Lu et al., 2005). When the tool is perpendicular to the work surface, both angles are equal to zero and the part of the cutting edge located close to the axis will move at very low speeds, causing plastic deformation of the surface and a rough surface finish.

In the case of a free-form, both angles can vary widely. Since a 3-axis machine cannot handle as wide a range of corrections to the tool inclination as a 5-axis center, an unacceptable surface finish must be expected (Merdol and Altintas, 2008). The most popular solution, which also prevents rapid tool wear when the angle becomes too small, is to reduce parameters such as feed and speed during strategy optimization. The feed is adjusted to control the force and cutting speed is adjusted to reduce the temperature (Kline et al., 1982; Li et al., 2004; Baskar et al., 2005; Seguy et al., 2008). For example, Yau and Kuo used a NURBS interpolation strategy to demonstrate that if the machine dynamic response is improved by feed-rate optimization, machining accuracy is improved and cutting time is reduced (Yau and Kuo, 2001). Sun et al., 2008 developed a guide spline-based feed-rate scheduling method for finish machining along curvilinear paths to improve the kinematic properties of the process and part geometry (Sun et al., 2008). Erkorkmaz et al. maintained a specified force level during the machining process by computing the work piece-tool engagement along the tool path and setting local feed limits (Erkorkmaz et al., 2013).

Because the solution negatively impacts the machining time and cost, the feed should be reduced only for the selected tool path components. Since optimization programs such as Vericut by CGTech or Production Module by ThirdWaveSystems use the volumetric rate to adapt the feed rate or spindle revolutions to the milling conditions while minimizing the performance of idle movements, the solution would be impractical to use without extensive support of a simulator integrated with CAM software (Wan et al., 2008; Kadir et al., 2011; Mao et al., 2011). The simulators improve accuracy of strategy optimization (Bohez, 2002; Li et al., 2004; Ratchev et al., 2004; Baskar et al., 2005; Wan et al., 2005). The optimized CNC code is executed in a much shorter machining time (up to 20–40% reduction can be accomplished), tool wear is reduced, and the quality of the work surface is improved.

There are, however, several issues associated with computer modeling and the application of simulators to NC code optimization, which increase the risk of surface damage and can cause accelerated tool wear. The simplest kinematic simulators operate on internal CAM code and can verify only the movements of a tool. The more advanced versions can operate on NC code generated from the internal code (Mao et al., 2011). NC code verification is more accurate, but because the simulation is often done in two dimensions, it is still not accurate enough for free-surface machining. Although the optimization program which operates on NC code can minimize idle movements and optimize cutting parameters, it cannot change the description of a tool geometric path. Another problem with the majority of CAM simulators is their limited ability to model the full dynamics of the machining process, which causes a significant discrepancy between the results calculated by various simulators for the same strategy (Kadir et al., 2011).

Those issues are particularly pronounced on a 3-axis CNC center to the point that it becomes impossible to justify its effectiveness for machining of a complex shape. The EV proposed in this paper addresses the limitations of standard simulators. It utilizes a similar approach as proposed by Erdm et al., who introduced the force-based feed rate scheduling strategy, in which radial, axial, and tangential cutting forces are modeled as functions of tool geometry, tool inclination angles, and cutting force coefficients. The strategy proved to reduce machining time and costs (Erdm et al., 2006). In contrast to the previous strategy, the force used by EV to control feed-rate is calculated by CAM software directly from the constitutive model, in which the flow stress is a function of strain hardening, strain rate sensitivity, and thermal softening (AdvantEdge (2010)).

On a 3-axis machine, the required feed reduction is more extensive than on a 5-axis machine. The strategy optimization for a 3-axis is more time consuming and the cost of process planning is higher because the EV algorithm must be executed to generate the required finish. Although a 5-axis center is more expensive to purchase, operate, and maintain (Quintana and Ciurana, 2011), the combined savings obtained from the lower tool wear, shorter planning, and machining time can significantly offset its amortization costs. In order to justify the cost effectiveness of a 3-axis CNC center for free-surface machining, all relevant costs for both alternatives have to be consistently examined based on a suitable cost assessment method.

2.2. Machining costs assessment methods

Due to fierce global competition, cost has become as critical as quality when a production process is created (Layer et al., 2002) and a machine tool is selected. Various decision models, supporting the selection of the most suitable alternative, are offered by existing research (Arslan et al., 2004; Gopalakrishnan et al., 2004). Some of the costs included in the models can be directly allocated to the end product – cost object. The other costs are usually collected in the cost centers and then allocated to the cost objects.

In cost accounting, the costs are accumulated at different levels to facilitate analysis at various levels of management. For example, the costs accrued during machining such as labor and machine hours, costs of tools and material (including the costs of rework and scrap), depreciation (CNC machine, CAD and CAM software, etc.), and overhead costs should be presented at various levels of aggregation, where development and machining phases are accumulated in their respective cost centers (Abdel-Malek and Asada-thorn, 1996; Diplaris and Sfantsikopoulos, 2000; Bouzzaz et al., 2006; Qian and Ben-Arie, 2008).

When the time of use is considered, the three different types of cost calculation can be defined: pre-, post-, and intermediate calculations. The first type allows for the forecasting of costs using high level estimation of fixed and variable costs, such as machine and labor hours and rates. For example, the cost of manufacturing M units can be expressed as the sum of fixed and variable costs, where fixed costs include setups, equipment depreciation, and others, while variable costs are the product of the number of units, the number of hours required to manufacture one unit, and the hourly labor/machine rates. Pre-calculation supports cost projection and is popular due to its simplicity, but the projection lacks accuracy. Post-calculation is based on the actual cost accounting data instead of estimates and standards. It is the most accurate, but unless extensive historical data is available, it cannot support the decision process during process planning stages.

The intermediate calculation is also based on estimates. However, in contrast to the first type, it requires more details in defining various costs elements, allocation methods and a well-structured generic model (Layer et al., 2002). For example, instead of using the total cost of the end unit to project the cost of an M-unit batch, the intermediate calculation will forecast the unit costs at every stage of planning/production, taking into account critical features and other factors which significantly impact the various types of costs and rates. The total cost projection will therefore be dependent not only on the batch size (M), but also on other factors.

The generic cost estimation model must be accurate, has to adapt easily to the continuous improvement of a process depicted by it, and
must allow for the representation of the complex product. Additionally, the cost structures must be described transparently. The accuracy of cost estimates depends on the number of factors, such as rates and unit costs included in the model. Since model complexity can have a negative impact on its practical application during a decision making process, only those cost elements that are above a materiality threshold, should be included. The materiality threshold can be established as a percentage of any given cost element against the total cost of a final production unit.

In order to satisfy the adaptability criterion, all micro planning activities in process planning, which can be subject to the proposed changes, must be identified. For example, if the change impacts any aspects of strategy definition in either CAD or CAM software, the definition and simulation/verification activities in strategy development and optimization must be depicted as separate micro planning activities. The same approach must be followed when the complexity criterion is considered. For example, if certain parameters such as surface finish are paramount to cost assessment, all factors that have direct impacts on the achievement of those parameters must be included in the model.

Out of many variants of cost estimation, only quantitative approaches, such as parametric, analogous, and detailed or generative-analytical models, show the cost structures with sufficient levels of detail to satisfy all of the aforementioned criteria (Asiedu and Gu, 1998). Generative-analytical models are based on a bottom-up method and depict the step-by-step accumulation of costs following the product creation phases (Bode, 2000). They are the most accurate in situations where the process links the product and its cost structure (Layer et al., 2002).

Resource Consumption Accounting (RCA), which is a modified/expanded version of the ABC accounting method, links the monetary values to the resources consumed during the various process steps (Baxendale and Foster, 2010). RCA is not based on the general ledger but focuses on the primary resources consumed instead, so it is ideal for the development of a generative-analytical model. RCA is very beneficial for short-term decisions and the analysis of the impact of changes in resource base, labor costs or demand on the overall budget (Mackie, 2006), as well as for high level managerial assessments (Baxendale and Foster, 2010). The cost effectiveness of 3- and 5-axis CNC machines is compared using an RCA method and a generative-analytical model developed in the next Section.

3. Theoretical models

3.1. Research approach

The research approach adopted in this paper consists of the following three steps:

Step 1 – Development of process planning and cost models (Sections 3.2 and 3.3).

First, the typical micro planning activities required to generate the NC code are arranged into a standard branch of the process planning model. The activities that are required to compensate for the limitations of a 3-axis machine are integrated into the standard planning activities and the enhanced branch of the process model is created. Second, the combined impact of the geometry, workpiece material properties, and cutting conditions on the cutting forces generated by the 3-axis CNC center is analyzed in CAM software. The physical behavior of workpiece material is represented by a constitutive model, from which the cutting forces are calculated by CAM – MES suite (AdvantEdge (2010)). The actual cutting forces are measured during the experiment and the material model is calibrated. Two versions of NC code are generated for a 3-axis process: first from the standard and the second from the enhanced branch. Finally, a cost model is developed using the accuracy, adaptability and complexity principles (Layer et al., 2002). The costs are assigned to activities similarly like in the RCA method (Folgado et al., 2010). The cost centers, pools and categories of the cost model are defined after Quintana and Ciurana (2011).

Step 2 – Technical verification (Section 5.1).

A turbine blade, which is one of the most challenging free-form objects to machine on a 3-axis CNC center, is selected for the case study. The blade is expensive to manufacture and since it is subjected to severe conditions, surface finish is paramount for its proper operation (Wang et al., 2010; Langmaak et al., 2013). Sa and Sv are chosen as the surface finish parameters (ISO 25178 and EUR 15178N). Sa is the most popular 3D parameter used when the cutting process is investigated (Quinsat et al., 2008). Due to its averaging nature, the parameter is stable, limits the impact of spurious spikes or scratches, and is often used as a manufacturing control parameter for feed adjustments (Stout et al., 1993). Sv indicates the maximum depth of the profile (valleys) below the mean surface and is useful to keep the cutting force within certain limits. Since the fracture propagation and material corrosion starts in valleys (Kamaya and Haruna, 2007), the parameter should be controlled very carefully when a free surface is cut in a hard-to-machine material. The parameters are measured by a 3D measurement device (Form Talysurf Intra from Taylor-Hobson) that is optimized for roughness analysis. The device uses a diamond point stylus, which sweeps the surface and a software program (Ultra) to treat the results. A square of 1 mm will be swept using a step of 1 μm in the X axis and 2 μm in the Y axis. Both the length and the cut-off wavelength of the low-pass filter will be set to 0.8 mm. The surface is carefully cleaned by air pressure to remove all dirt prior to each measurement. The measurements are repeated at least three times to calculate the average values.

Step 3 – Cost assessment (Section 5.2).

A convenience sample of 10 companies is established to collect data about labor, machine, and scrap rates for the machining phase. The convenience sample is used because of the confidential nature of data. Such sensitive accounting data can be reliably collected only from the sources, for which a high level of mutual trust was developed during long-term collaboration. The sample size is considered sufficient because (i) the data were required to demonstrate that a range of parameters, within which it makes sense to use 3-axis machining for a free form application, can be established (not to prove statistical validity), and (ii) a response return rate of hundred percent of and high reliability was expected. The rates for the planning phase are established using the catalog prices of CNC machines, software, and experimental equipment. The overhead costs (cutting fluid, energy, etc.) are included in the rate for equipment. The time durations of various micro planning activities are measured during the case study. The average cost of tools is calculated using the catalog prices for 2013. The average number of tools is derived using the tool wear experiments.

3.2. Enhancing strategy optimization with experimental verification

The two standard activities of process planning are strategy development (SD) and strategy optimization (SO). They are depicted in the process planning model (Fig. 1) by symbols outlined with continuous lines. The branch that represents the standard process planning is depicted by the continuous arrows. The NC code for a 5-axis machining was generated from that standard branch. In order to generate the improved NC code for a 3-axis machine, the standard
branch was enhanced with the additional micro planning activities, which belong to EV and are interwoven into SO. The enhanced branch is depicted in Fig. 1 with the dashed arrows.

SD begins when the geometry model and initial values of production process data, such as machining parameters and $R_{\text{Max}}$, are inputted into the CAM software. SD consists of the following two micro planning activities: strategy definition and kinematic simulation. These activities are the same in both standard and enhanced branches. The tool paths are defined in CAM software during the strategy definition. The objective of kinematic simulation is to verify the strategy for collisions and to find the path, which gives the shortest machining time, $t_{\text{Mach}}$, and the acceptable level of surface Roughness, $R$. The NC code generated for the selected strategy will be adjusted during the last micro planning activity of SO.

SO consists of the following two standard micro planning activities: physical process simulation and optimization/adjustment of control parameters. The objective of physical process simulation is to generate the table $[F] = [F_{\text{standard}}]$, which consists of cutting forces calculated for the critical parameters along the tool path. The table is used during optimization/adjustment of a selected control parameter to keep the tangential cutting forces within the predefined limits. The calculations are based on the standard Material Model (CAM), which includes constitutive model of the physical properties of the machining environment and FE network. In the process planning model, $f$ is the control parameter, so the upper/lower limits of feed ($f_{\text{min}}$, $f_{\text{max}}$) together with the critical values of the other machining parameters are determined from the NC code as the first input into the physical process simulation. The coefficients in the constitutive model and FE network parameters are the second input. The force limits ($F_{\text{Min}}$, $F_{\text{Max}}$) are the last input. The standard process is concluded with the generation of an optimized NC code.

The objective of physical process simulation in the enhanced branch is the same: to generate the table $[F] = [F_{\text{enhanced}}]$, which consists of cutting forces calculated for the critical parameters along the tool path. However, it is highly possible that the cutting forces...
derived using the standard Material Model (CAM) are different from the cutting forces observed during the actual machining process. If those differences are significant, then the adjustments made during the optimization of control parameters will be incorrect. To that end, the NC code generated at the conclusion of SO will cause loss of stability and inferior surface finish can be expected. Therefore, [F\text{enhanced}] must more accurately depict the machining environment than [F\text{standard}].

EV begins with the experiment, in which the tangential cutting forces are measured during (i-1) experimental cuts performed over a straight line in the same material as the workpiece. Each cut is repeated three times and the average is saved as [F\text{obs}], which is the first input into the EV algorithm. The depth of cut and speed are calculated as averages from the same values of the other machining parameters as the ones used by the standard branch. They remain the same for each experimental cut. The feed rates for each cut are calculated as \( f_{i+1} = f_i + \left( f_{\text{max}} - f_{\text{min}} \right)/i \).

The objective of the EV algorithm is to calibrate the standard Material Model included in CAM simulator. The calibration includes refinement of FE network parameters (minimum/maximum element size, net density, mesh refinement factor, mesh coarsening factor, and maximum number of nodes) and modification of coefficients in force equations, which represent attributes such as work hardening, thermal response, and strain rate sensitivity. At this stage of research, the calibration is conducted manually in CAM (AdvantEdge (2010)). During the calibration process, [F\text{cal}] is compared to the table [F\text{cal}], which is derived for the same set of (i+1) machining parameters using a standard physical process simulation (CAM). The comparison is based on the following formula \( (F_{\text{cal}} - F_{\text{obs}})/F_{\text{cal}} < FC \), where the coefficient FC determines the proximity of \( F_{\text{cal}} \) to the actual experimentally observed \( F_{\text{obs}} \). The calibration loop is marked with double-line arrows and is repeated until the condition is fulfilled. When the calibration is complete, the calibrated Material Model is used to generate [F] = [F\text{enhanced}] during the physical process simulation, which is conducted again. The remaining micro planning activities in both branches are the same. The only difference is that for a 3-axis machine, [F\text{enhanced}] instead of [F\text{standard}] is used to control feed.

\( FC \) represents the permissible deviation from the accuracy of the force calculations. If \( FC \) is small, the calibration process will require a large number of iterations, which will increase the time required for an experimental verification stage. If \( FC \) is large, the duration of EV will be reduced but the number of potential issues during machining process, which can lead to increased risk of workpiece damage and a high scrap rate (RSC) generated during the machining phase, will be much higher. In Fig. 1 the loop which needs to be repeated in order to “train” the material model in CAM is marked with the red double-line arrows. Although each iteration takes less time, they also generate significantly less improvement in RSC – the condition commonly known as the learning effect (Jaber and Khan, 2010). To that end, RSC is linked to the duration of EV using the learning curve model, which is further discussed in Section 3.3.

3.3. Cost model

The cost of micro planning activities along the enhanced branch in the process planning model is depicted by Eq. (1). Since EV is not required for 5-axis machining, only strategy development and strategy optimization costs are included in Eq. (1a).

\[
\begin{align*}
\text{Cost Planning}_{3-\text{axis}} &= \text{Cost}_{SD} + \text{Cost}_{SO} + \text{Cost}_{EV} \\
\text{Cost Planning}_{5-\text{axis}} &= \text{Cost}_{SD} + \text{Cost}_{SO} 
\end{align*}
\]

Although different equipment rates for each activity are required, the same operator performs them all, so a single labor rate is used. If the hourly labor and machine rates for Operator and Equipment/Machine Tool are defined as \( R_{\text{RO}} \) and \( R_{\text{RM}} \) respectively and \( t \) represents the activity duration, the cost of activity can be depicted as

\[
\begin{align*}
\text{Cost}_{SD} &= (R_{\text{RO}} \cdot SD + R_{\text{RM}} \cdot F_{\text{plan}}) \cdot t_{\text{SD}} \\
\text{Cost}_{SO} &= (R_{\text{RO}} \cdot SO + R_{\text{RM}} \cdot F_{\text{plan}}) \\
\text{Cost}_{EV} &= (R_{\text{RO}} \cdot EV + R_{\text{RM}} \cdot F_{\text{plan}} + R_{\text{RM}} \cdot Mach) \cdot t_{\text{EV}} 
\end{align*}
\]

The machining comprises of roughing and finishing. If \( RM \) is the cost of 1 kg of Raw Material, \( CT \) represents average cost of one tool and RSC is the cost of scrap, the total cost of machining phase (2nd cost center) is depicted in the following equation:

\[
\text{Cost Machining} = |RM| \cdot W + (R_{\text{RO}} \cdot Mach + R_{\text{RM}} \cdot Mach) \cdot (t_{\text{Mach Rough}} + t_{\text{Mach Finish}} + 2t_{\text{Setup}}) + CT \cdot NT \cdot (1 + R_{\text{C}}) 
\]

(2)

RSC is the coefficient, which represents the highest risk of damaging the surface when a single unit is machined in the maximum scrap rate when multi-item batches are produced. It can be calculated as the ratio between the numbers of the parts completed at an acceptable quality to the number of parts, for which any of the selected roughness parameters is below the acceptable level, so it stays within the range of [0, 1]. In the case of a 3-axis machine, the scrap rate depends on the duration of the experimental verification stage \( (t_{\text{EV}}) \), which provides the feedback loop and facilitates quality improvement through the same mechanism as defined by the learning or performance improvement curves (Jaber and Guiffrida, 2004; Jaber and Khan, 2010; Khan et al., 2014). We will calculate the scrap rate from Eq. (3) following a similar approach as depicted in Plaza and Turekten (2009) and Plaza et al. (2010).

\[
RSC_{3-\text{axis}} = RSC_{\text{Max}} \cdot e^{-k_{\text{EV}}} 
\]

As already discussed, all parts made on a 3-axis machine will have unacceptable surface finish if an experimental verification phase is not used to improve the NC code, so \( RSC_{\text{Max}} = 1 \) (100%), which transforms the Eq. (3) into its simpler form:

\[
RSC_{3-\text{axis}} = e^{-k_{\text{EV}}} 
\]

(4)

In order to assess the Coefficient \( k \) in Eq. (4), the minimum number of hours of experimental verification that yield the acceptable surface finish, \( t_{\text{EV Min}} \), must be known. Eq. (4) can be depicted as \( RSC_{3-\text{axis}}(t_{\text{EV Min}}) = e^{-k_{\text{EV}} \cdot t_{\text{EV Min}}} \), from which \( k \) can be calculated as

\[
\begin{align*}
RSC_{3-\text{axis}} &= e^{-k_{\text{EV}} \cdot t_{\text{EV Min}}} \\
\ln(RSC_{3-\text{axis}}(t_{\text{EV Min}})) &= -k_{\text{EV}} \cdot t_{\text{EV Min}} \\
\end{align*}
\]

When Eq. (5) is substituted into Eq. (4), we get

\[
RSC_{3-\text{axis}} = e^{\frac{\ln(RSC_{3-\text{axis}}(t_{\text{EV Min}}))}{t_{\text{EV Min}}}} 
\]

(6)

EV is not used for a 5-axis machine so the single scrap rate value \( RSC_{5-\text{axis}} \) can be used.

Assuming that the costs of geometry definition in CAD are identical in both cases, they can be excluded from the comparative analysis. If \( M \) is a number of parts (turbine blades) in one batch, the total cost of manufacturing one batch, can be depicted as

\[
\begin{align*}
\text{Total Cost} &= \text{Cost Planning} + M \cdot \text{Cost Machining} \\
\text{Total Cost}_{3-\text{axis}} &= \text{Cost}_{SD} + \text{Cost}_{SO} + \text{Cost}_{EV} + M \cdot |RM| \cdot W + (R_{\text{RO}} \cdot Mach + R_{\text{RM}} \cdot Mach) \cdot (t_{\text{Mach Rough}} + t_{\text{Mach Finish}} + 2t_{\text{Setup}}) + CT \cdot NT \cdot \left(1 + e^{\frac{\ln(RSC_{3-\text{axis}}(t_{\text{EV Min}}))}{t_{\text{EV Min}}}}\right) 
\end{align*}
\]

(7)
After substituting Eqs. (1a) and (2), and $RSC_5/CO$ into Eq. (7), it can be transformed into a cost equation for a 5-axis machine.

$$\text{Total Cost}_{5-axis} = \text{Cost}_{SD} + \text{Cost}_{SO} + M|RM W + (RRO_{Mach} + RR\text{E}_{Mach}) \\
\times (t_{\text{Mach Rough}} + t_{\text{Mach Finish}} + 2t_{\text{Setup}}) + CT NT(1 + RSC_{5-axis}). \quad (8a)$$

4. Case study

4.1. Strategy development

Since it is cumbersome to create the free form surface directly in CAD software, the geometry of an actual blade (Fig. 2) was scanned, saved as the cloud points, and imported to CAD software (CATIA v5R16 developed by Dassault Systemes). Strategies for tool paths were built using CAM software – ESPRIT – from DP Technology assuming a ball end mill (12 mm radius), for which the optimal inclination angle to the machined surface is 12°. The cuboidal shaped blank from which all redundant material was to be removed by roughing was chosen. Seven potential strategies for 3-axis machining were considered: ellipse, level z, square, spiral, circle, zigzag 1 and zigzag 2. The strategy that offered the shortest machining time for finishing was Ellipse and the Level z strategy was chosen for rough machining.

The following parameters were used for rough and finish machining as recommended by industry standards: cutting speed – 70 m/min, feed – 0.06 mm/edge. The parameters are within the acceptable ranges recommended by the tool manufacturers of solid carbide end mills with ball head shape. In the case of a 5-axis machine, the speed variation around the recommended level was not expected to be significant. For a 3-axis machine, the cutting speed varied within the range (0–70) m/min. The variation of feed ($f_{\text{min}}; f_{\text{max}}$) was expected to be within the range of (0.02; 0.12) mm/edge. During rough machining, axial and radial depths of cuts were 3 mm and 2 mm correspondingly. For finish machining, axial and radial depths of cuts were expected to vary within the range of (0.5–1.3) mm and (0.25–0.35) mm, respectively, depending on the shape of allowance left after rough machining.

<table>
<thead>
<tr>
<th>i</th>
<th>Feed [mm/edge]</th>
<th>$F_{\text{obs}}$ [N]</th>
<th>$v_c=70$ m/min</th>
<th>$a_t=0.5$ mm</th>
<th>$a_r=0.3$ mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.02</td>
<td>38</td>
<td>$a_t=0.5$ mm</td>
<td>$a_r=0.3$ mm</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.04</td>
<td>82</td>
<td>$a_t=0.5$ mm</td>
<td>$a_r=0.3$ mm</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.06</td>
<td>147</td>
<td>$a_t=0.5$ mm</td>
<td>$a_r=0.3$ mm</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.08</td>
<td>187</td>
<td>$a_t=0.5$ mm</td>
<td>$a_r=0.3$ mm</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.10</td>
<td>227</td>
<td>$a_t=0.5$ mm</td>
<td>$a_r=0.3$ mm</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.12</td>
<td>240</td>
<td>$a_t=0.5$ mm</td>
<td>$a_r=0.3$ mm</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 Results of experimental cuts [$F_{\text{obs}}$].

Fig. 2. Geometry model of a turbine blade.

Fig. 3. Calibration of material model.

Fig. 4. The cutting force (left) and removal rate (right) during the simulation of finishing.

Fig. 5. Spots selected on a blade for surface finish assessment.
4.2. Experimental verification and strategy optimization

The experimental cuts were performed for \( i + 1 = 6 \) feed rate values. Kistler piezoelectric-multicomponent dynamometer (type 9257B) was used to measure the tangential cutting force. Each cut was repeated three times and the average values of each element of table \( F_{\text{obs}} \) were calculated. The results are summarized in Table 1.

Material model in CAM was calibrated for finish milling in CAM – MES suite, in which the FE network was modeled using a Lagrangian FE code (AdvantEdge (2010)). The workpiece material was modeled as thermo-elastic-plastic, for which the flow stress is a function of strain hardening, strain rate sensitivity, and thermal softening. The critical coefficients in the material model for the alloy steel EN 34CrNiMo6, which was selected for the blade, are depicted in Table A1 and A2, while the properties of sintered carbide are summarized in Table A3 (Appendix A). The \( FC \) coefficient was set at 0.1, so a 10% discrepancy between calculated and observed forces was allowed. The three iterations, which are depicted in Fig. 3 as Sim1, Sim2, and Sim3, were required to calibrate the model.

Sim1 took 3.5 h and reduced the discrepancy between observed and calculated forces down to the 35–45% range. Sim2 took additional 2 h and reduced the discrepancy to 15–25% range. After Sim3, which
took approximately 1.5 h, the calculated and observed forces were below the required 10% discrepancy. The total time required for the three iterations of the EV algorithm, \( t_{EV} \approx 7 \) [hours].

The calibrated material model was used in the Physical Process Simulation to build \( F_{enhanced} \). \( F_{standard} \) was generated as a baseline. The maximum and minimum limit values for a tangent cutting force was set as \( F_{min} = 8 \) N and \( F_{max} = 30 \) N. Two versions of the NC code were generated at the conclusion of the SD for a 3-axis machining center HAAS-VF1: Version 1 was generated using \( F_{standard} \), while Version 2 was optimized based on \( F_{enhanced} \). The execution of both versions was simulated in CAM in order to analyze the cutting forces along the entire tool path. They are depicted in the upper portion of Fig. 4 as functions of machining time.

The dots indicate areas where tangent force for Version 1 reaches high values significantly exceeding the 30 N limits and even reaching over 100 N. As a result, a significant deterioration of surface quality has to be expected. Note that for Version 2 the cutting force is never larger than 30 N. Additionally, since the machining time for Versions 1 and 2 are 96.3 [min] and 79.6 [min] respectively, the reduction of over 17% of machining time was accomplished due to EV. Those benefits can be attributed to the improvement of decohesion process and corresponding reduction of plastic deformation in the work material during chip creation and flow, which is a result of increased cutting force stability. The benefits are confirmed during the quality verification in Section 5.1.

5. Discussion of research questions.

5.1. Quality assessment

The two surface finish parameters were examined at nine spots of a blade surface (Fig. 5).

Both parameters were expected to be at the acceptable level in the areas where diagonally-positive down milling was used and the low inclination angle was avoided (spots 1, 3, 5, and 6). The inferior quality due to reduced stability of the workpiece was expected in spots 2, 4, and 7, which are located the furthest from the clamp. Unacceptable finish caused by the very small inclination angle was expected in spots 8 and 9, where an active cutting edge is close to the tool axis and the cutting speed is drastically reduced.

In Fig. 6, the black and gray bars represent the results of surface finish assessment for Versions 1 and 2 respectively. The limit values of the chosen surface roughness parameters, \( S_v \) and \( S_a \), were chosen to be 3.0 and 0.75 \( \mu \)m respectively, which represent the required quality level for a free surface machined on a 5-axis center. For Version 1, both quality parameters are outside the required limits. Due to the loss of stability and vibrations, the worst results were recorded in spots 2, 4, and 7.

For Version 2, both parameters are within the required levels in all spots except 8 and 9 because EV did not improve the surface finish in the areas machined with a very small inclination angle. The feed reduction was not sufficient to compensate for the low peripheral speed at the active cutting edge. The limitation of the EV algorithm discovered by the case study will be corrected in its next version, in which the feed reduction will be correlated with the increase of the cutting speed in the areas where the inclination angle approaches zero.

The best improvement was achieved in spot 4. Its photos taken after machining with either Version 1 or 2 of the NC code are presented in Fig. 7. When Version 1 is used, significant friction and plastic deformation causes the increase in both temperature and cutting force, which leads to accelerated wear of the cutting edge. The irregular traces of machining, which are caused by vibrations and plastic deformations of the workpiece are clearly visible. The

| Table 2 |
| Costs and rates derived for a single-unit (2 sides of one blade) batch. |
| Option | 3-Axis CNC | 5-Axis CNC |
| Rate of tool \( \] \$[h] | CT | 6.25 | 7.5 |
| No. of tools | NT | 1 | 1 |
| Scrap rate \% | RSC | 12 | 4 | N/A |
| Learning coefficient | k (Eq. (5)) | 0.3 | N/A |
| Material unit cost \$/kg | RM | 1.9 |
| Material quantity [kg] | W | 0.38 |
| Average rates from Table 4 \$/h] | \( R_{R_o Mach} = 36 \) | \( R_{R_o Mach} = 12 \) |
| Times [h] | \( t_{Mach} Finish \) | 7 |
| Average cost of tool \$ | CT | 6.25 |
| Scrap rate \% | RSC | 12 | 4 |
| Learning coefficient | k (Eq. (5)) | 0.3 |
| Table 3 |
| Summary of data collected from the companies responding to the questionnaire. |
| Number of employees | Type of CNC machine tool | Scrap RSC [\%] | Equipment and operator rates for machining phase \$/h] | \( R_{R_o Mach} = 36 \) | \( R_{R_o Mach} = 12 \) |
| Company | 0–20 | 21–50 | Over 50 | 3-axis | 5-axis | 3-axis | 5-axis |
| 1 | x | x | 15 | 25.5 | 12 |
| 2 | x | 17 | 16 | 10 |
| 3 | x | x | 11 | 35 | 13 |
| 4 | x | x | 4.5 | 49 | 14 |
| 5 | x | x | 8 | 66.5 | 14 |
| 6 | x | x | 3 | 125 | 17 |
| 7 | x | x | 10 | 38 | 12 |
| 8 | x | x | 11 | 35 | 11 |
| 9 | x | x | 8.5 | 52 | 14 |

| Table 4 |
| Average, minimum and maximum rates from Table 3. |
| Rates \$/h] | Machine \( R_{R_o Mach} = 36 \) | 3-axis | 5-axis | 3-axis | 5-axis |
| Average | 36 | 12 | |
| Minimum – older machine (dashed line in Fig. 9) | 16 | 10 | 17 | 4.5 |
| Maximum – newer machine (continuous line in Fig. 9) | 66.5 | 125 | 8 | 3 |
machining traces are much more regular when Version 2 of the NC code is used.

5.2. Analysis of cost effectiveness

5.2.1. Summary of cost accounting data

The variables in Eqs. (8) and (8a) were determined using the average prices from the polish market registered during 2013 (Table 2).

The dimensions of a blank are 18 mm x 30 mm x 90 mm. The cost of material, \( RM = 1.9 \) $/kg, represents the value of alloy steel EN34CrNiMo6. The material quantity, \( W \), is calculated as a product of blank volume (0.0486 dm\(^3\)) and density of the steel (7.85 kg/dm\(^3\)).

The following assumptions were made for the calculation of the planning phase rates:

(a) cost of purchase plus 10-year upgrade of CAM software: $15,600 ($20,500) for 3- (5-) axis,
(b) cost of purchase plus 10-year upgrade of SIM software: $29,000 ($40,800) for 3- (5-) axis,
(c) year amortization (20,000 h),
(d) cost of equipment for experimental verification, which included force measurement system plus software ($60,000),
and a 5 year amortization (10,000 h).

The machining phase rates were calculated based on the results of the questionnaire (Tables 3).

The time durations for the planning phase were recorded during the case study. In order to examine the impact of EV duration (\( t_{EV} \)), two options for a 3-axis machine were examined: Option 1 and Option 2. As discussed in Section 4.2, training of a material model to the level required for an acceptable surface finish took 7 h, so \( t_{EV \ option \ 1} = 7 \) h. As discussed in Section 5.1, the NC code is sufficiently improved after that time to compensate for the quality issues caused by the shape complexity. Therefore, the average scrap rate for a 3-axis machine (\( RSC = 12\% \)) was assumed for Option 1.

The purpose of adding Option 2 was to examine how much additional time beyond the necessary 7 h of EV, and its associated increased cost, is required to reduce the scrap rate on a 3-axis machine from 12% to 4% (average level for a 5-axis machine in Table 2). \( t_{EV \ option \ 2} \) can be assessed from Eq. (8), in which the learning curve was constructed using Eq. (6). EV duration at which the risk of producing the unacceptable surface quality is 4% equals 11 h.

The durations of the machining phase were derived from the CAM software.

The average cost of the tool in Table 2, CT, represents the cost of a portion of the tool life required to machine the two sides of one blade. The tool can be used 6 times, assuming that it can be re sharpened up to 5 times, in which case \( CT = C_{Tool}/(6 \times (ToolLife/T_Mach)) \), where \( C_{Tool} \) represents the total cost of purchase and re sharpening. \( ToolLife \) is the average machining time until the tool must be re sharpened. \( C_{Tool} \) was assessed to be $150 or $180 (for 3- or 5-axis tools, respectively). Based on the tool wear tests \( ToolLife_{min} \) was determined to be 800 min or 650 min (for 3- or 5-axis, respectively).

5.2.2. Results and discussion

In order to streamline the time-consuming calculations required during the analysis, the cost model was expanded into a prototype decision support system (DSS) developed in Excel. The planning and machining costs calculated by DSS for the three options are summarized in Table 5, which allows for the comparison of the cost effectiveness of 3- and 5-axis machines. In Fig. 9, the costs are presented in the chart, which was also printed by the reported DSS.

The following two observations can be made from these results: (1) the costs of EV are high when compared to the other planning and machining costs, and (2) the costs of the scrap rate are very small when compared to EV costs. The observations lead to only one conclusion: the benefits of improved quality cannot offset the costs of EV for a small batch. The EV cost must be treated as a fixed cost. In order to reduce its per-unit contribution, it must be distributed among a high quantity of blades made using the same setup.

In Fig. 10, the combined costs of the planning and machining phases are depicted as a function of batch size. The fixed costs of planning for Options 3, 1, and 2 ($62.2, $447, and $732, respectively) are depicted as the starting points for the graphs.

The previous conclusion is confirmed. For up to six-unit batches (intersection of continuous lines), it is more beneficial to use the more expensive 5-axis machine. Option 1 becomes more beneficial when more than six units are to be manufactured. Option 2 is the most expensive alternative. The benefits of using a 3-axis machine outweigh the costs of a 5-axis machine only after 8 blades are to be made using the same setup. The extension of EV

---

**Table 5**

<table>
<thead>
<tr>
<th>Costs ([$])</th>
<th>3-axis CNC</th>
<th>5-axis CNC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Planning phase</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Costso</td>
<td>316</td>
<td>40.1</td>
</tr>
<tr>
<td>Costso</td>
<td>1645</td>
<td>22.15</td>
</tr>
<tr>
<td>Costso</td>
<td>399</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Cost Planning</strong></td>
<td>447</td>
<td>684</td>
</tr>
<tr>
<td><strong>Machining phase</strong></td>
<td>732</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Labor</strong></td>
<td>42.96</td>
<td>42.9</td>
</tr>
<tr>
<td><strong>Machine</strong></td>
<td>128.9</td>
<td>200.2</td>
</tr>
<tr>
<td><strong>Raw material</strong></td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td><strong>Tools</strong></td>
<td>6.25</td>
<td>7.5</td>
</tr>
<tr>
<td><strong>Cost Machining</strong></td>
<td>178.8</td>
<td>251.3</td>
</tr>
<tr>
<td>**Cost Machining ((1+RSC_{Max}))</td>
<td>200.7</td>
<td>185.4</td>
</tr>
<tr>
<td></td>
<td>261.4</td>
<td></td>
</tr>
</tbody>
</table>
required to reduce the scrap rate from 12% to 4% can only be justified for batches larger than 13 blades.

In order to assess the duration of EV at which the scrap rate costs will offset the combined costs of planning and machining, the scrap rate costs are depicted in Fig. 11 as functions of $t_{EV}$ for three batch sizes: 10 units, 20 units and 30 units (continuous, square dotted, and dashed lines respectively).

The corresponding costs of the scrap rate for a 5-axis machine are also depicted for comparison. Points A1 and A2 demonstrate the number of EV hours at which the costs of the scrap rates for both machine types are the same. Note that although the scrap rate of 4% can be accomplished after approximately 11 h (Fig. 8), due to the lower machine costs for a 3-axis machine, the scrap rate costs are balanced for both machine types at a smaller number of hours (approximately 9.5 hours). This means that if the assessment was made based on costs of quality only, the impacts of EV on the comparative cost effectiveness of a 3- versus 5-axis machine would be even stronger.

The EV and planning costs are also depicted in Fig. 11 as functions of $t_{EV}$ (double and triple lines respectively). Points B1 and B2 (intersection with double line for 20- and 30-unit batches respectively) illustrate the numbers of EV hours at which the EV cost can be offset by the reduction in the scrap rate. The intersections with the triple line (points C1 and C2) illustrate the number of EV hours at which the total planning costs can be offset by the reduction in the scrap rate. Note that although for a 10-unit batch, the scrap rate reduction will offset only a small fraction of those costs, for a 20-unit batch, the total planning costs will be paid off if 7 h are used. This means that even if the costs of material and labor are relatively low, it makes sense to invest in NC
The analysis conducted up to this point was based on average rates, but in Table 2 all rates vary widely. For a 3-axis machine, the hourly equipment rates are within the range of $16–66.5 and the hourly labor rates are within the $10–14 range. For a 5-axis machine, the hourly equipment rates are within the $49–125 range and the hourly labor rates are within the $14–17 range. The variation can be explained by the fact that the older machines were amortized completely while the more advanced/newer machines are more expensive, necessitate that amortization is included in the rate calculation, and require more skilled operators than their old counterparts.

The sensitivity analysis, in which the ranges for the rates and bases are used instead of their average values, was conducted to examine their impact (Fig. 12). The continuous lines depict the combined costs of planning and machining as functions of batch size when the most expensive and not yet amortized 3- and 5-axis machines are used. They indicate the upper limits for our analysis. The dashed lines depict the similar functions constructed for the least expensive and fully amortized 3- and 5-axis machines. They indicate the lower limits for the analysis.

The points of intersection indicate the tolerance limits for the results derived from Fig. 11 (Option 1 becomes more beneficial when more than six units are to be manufactured). The 5-axis machine is the most advantageous option if a single-unit batch is to be manufactured. For 1–2-unit batches, the 5-axis machines may be more cost effective than any other alternative. If more than three units are to be manufactured within a single batch, the fully amortized 3- or 5-axis machines should be used. It makes sense to purchase new equipment only if the existing machines need to be replaced. The company should invest in a 5-axis machine if less than 6-item batches are to be manufactured. Due to the currently very high cost of EV, the investment in a 3-axis machine should be made only if more than 7-item batches are to be manufactured.

6. Conclusion

The recent advancements in tool development allow for the increases precision of machining processes (Wang and Mathew, 1995; Ratchev et al., 2004; Bravo et al., 2005; Lu et al., 2005; Rao and Rao, 2006) and the use of cutting tools in situations where cutting allowances are small (Wan et al., 2008). The argument for using a 5-axis CNC center to machine complex shapes in hard-to-cut materials is well supported. The evidence, such as: better control of tool position, efficient utilization of tools, reduction of machining time, and a shorter process planning phase, are very convincing. However, computer modeling has become a powerful tool and CAM software supports engineers during planning and machining phases.

This paper challenged the assumption that a 3-axis center cannot compete under such overwhelming circumstances. The study proposed to combat the deficiencies of 3-axis centers, which are still being used extensively by the industry, with the sophisticated application of advanced software and computer modeling. It demonstrated that a free-form complex shape can be manufactured on a 3-axis machine if EV is integrated with the currently used process. In the study, the finish of the machined surface was improved almost two times making it comparable with that typically produced by a 5-axis machine. An additional benefit of using the experimental verification was the ability to reduce machining time by 17%.

EV generates marginal cost benefits from the reduction in the scrap rate, which can partially offset the costs of the additional activity when large batches are to be manufactured. However, for a certain critical size, the machining and planning costs/benefits reach a break-even point for both alternatives. If a batch size exceeds that critical number, then even with the additional cost of experimental verification, a 3-axis machine is the most cost-effective option. The decision model developed by this study allows engineers to find that critical batch size. The calculations required to complete the cost/benefit analysis are cumbersome and time-consuming so the study offers a decision support system developed in Excel to streamline the decision-making process.

In order to justify the application of EV and convince the industry that a 3-axis center can be as cost effective as a 5-axis one for machining small batches of complex shapes, the EV algorithm must be improved and the time required to calibrate the material model must be reduced. The next version of the EV algorithm will also address the missing correlation between the feed reduction and the required increase in cutting speed in the areas where the inclination angle approaches zero, which contributes to the issues uncovered by the case study.

Appendix A

See Appendix Tables A1–A3.
Table A1
Chemical composition of alloy steel EN 34CrNiMo6.

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.65</td>
<td>Max 0.4</td>
<td>1.5</td>
<td>1.5</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Table A2
Physical and mechanical properties of alloy steel EN 34CrNiMo6 at room temperature.

<table>
<thead>
<tr>
<th>Density, ρ (kg/dm³)</th>
<th>Melting point, Tₘ (°C)</th>
<th>Thermal conductivity, k (W/m K)</th>
<th>Modulus of elasticity, E (GPa)</th>
<th>Specific heat, c (J/kg·K)</th>
<th>Ultimate tensile strength, σₘₜ (MPa)</th>
<th>Yield strength, σ₀ (MPa)</th>
<th>Hardness (Bhn)</th>
<th>Poisson’s ratio, ν</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.85</td>
<td>1450</td>
<td>38</td>
<td>206</td>
<td>460</td>
<td>1000</td>
<td>750</td>
<td>300</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table A3
Physical and mechanical properties of sintered carbide (Al-Zkeri et al., 2009).

<table>
<thead>
<tr>
<th>Density, ρ (kg/dm³)</th>
<th>Thermal conductivity, k (W/m·K)</th>
<th>Modulus of elasticity, E (GPa)</th>
<th>Specific heat, c (J/kg·K)</th>
<th>Hardness (HV)</th>
<th>Poisson’s ratio, ν</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.9</td>
<td>45 (for 20 °C)</td>
<td>520</td>
<td>398</td>
<td>1550</td>
<td>0.22</td>
</tr>
</tbody>
</table>

References


