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A framework for machining optimisation based on STEP-NC

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Abstract Inappropriate machining conditions such as cutting forces cause tool failures, poor surface quality and worst of all machine breakdowns. This may be avoided by using optimal machining parameters, e.g. feed-rate, and continuing to monitor it throughout the machining process. To optimize feed-rate, we propose a system that consists of an optimisation module, a process control module and a knowledge based evaluation module. STEP-NC is the underlying data model for optimisation. Given the nominal powers, the cutting force can be estimated based on the higher-level production information such as workpiece properties, tool materials and geometries, and machine capabilities. The main function of the Process Control module is process monitoring and control. The output is the desired actual feed-rate. Finally, the actual feed-rate is recorded and evaluated in the Knowledge Based Evaluation module.

Keywords Machining optimisation · Cutting force · Feed-rate · Machine condition monitoring · STEP-NC

Symbol	Definition (Unit)
$a_{\min}$	Minimum depth of cut (mm)
a_s	Average depth of cut (mm)
$a_{\max}$	Maximum depth of cut (mm)
$a_{\text{allowable}}$	Depth of cut permitted by machine (mm)
a_t	Total depth of cut (mm)
b_w	Workpiece width or cutting width (mm)
c	Constant
d_{si}	Different types of face-milling
d_{s1}	Full-face milling type
d_{s2}	Unidirectional part-face type
d_{s3}	Bilateral part-face type
e	Distance of overlapping (mm)
η_m	Mechanical efficiency
F_{mt}	Total mean tangential milling force (N)
$f_s^{\min}$	Minimum feed-rate (mm/min)
f_s	Feed-rate (mm/min)
$f_s^{\max}$	Maximum feed-rate (mm/min)
f_{s1}^{opt}	Optimum feed-rate for time-critical (mm/min)
f_{s2}^{opt}	Optimum feed-rate for quality-critical (mm/min)
f_z	Feed per tooth (mm/r)
f_{mz}	Allowable feed mechanism (mm/min)
$h_{m(\chi)}$	The mean chips thickness (mm)
k_s	Specific cutting resistance (N/mm^2)
l_m	Total travel at whole features path (mm)
N_m	Main drive motor power (kW)
N_{mc}	Predicted motor power (kW)
N_c	Cutting power (kW)
n	Milling cutter rotational speed (rpm)
R_t	Peak-to-valley surface roughness (μm)
R_a	Arithmetic surface roughness (μm)
$\overline{R}_a$	Arithmetic average surface roughness (μm)
r_t	Tool nose radius (mm)
t	Chips thickness (mm)
t_m	Machining time (min)
t_{s1}^{opt}	Optimum machining time for time-critical (min)
φ_1	Entrance angle (deg)

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φ_2 Exit angle (deg)
$\overline{\varphi}_c$ Contact angle in horizontal milling (radians)
V_c Cutting speed (m/min)
χ Setting angle (deg)
Z_c Number of cutting teeth

Introduction

In the machining domain, over-loading of spindle torque, excessive cutting force, chatter, tool wear and other constraints may lead to major problems such as tool breakage and product quality deterioration. These problems increase the cost of a product so that it becomes less competitive in the market. Machine tools need to be re-designed for process optimisation, monitoring and control so as to increase productivity, reduce production time and cost, improve defective part and relax machine constraints (Li et al. 2004). For intelligent machining, the machine system can achieve not only adaptive control and monitoring in-process tool life measurement but also provide supervision of machining operations in terms of best machining setup (Malakooti et al. 1995).

To reduce production costs and guarantee sustained product quality, it is necessary to keep tolerances checked as well as actively monitor machine tool conditions. Tool wear and surface roughness are commonly used as sources of information about machine tool conditions (Saglam and Unuvar 2003). Surface roughness depends on a number of process parameters such as feed-rate, cutting speed, axial-radial depth of cut, and machining irregularities such as chatter, excessive cutting force, tool wear, workpiece material properties and fluid (Ghani et al. 2004; Öktem et al. 2006). Empirical models have been developed to predict surface roughness in terms of process parameters that include hardness, feed-rate, point angle, depth of cut and spindle speed for finished turning using a statistical regression technique (Feng and Wang 2002). To maintain product quality with tight tolerances, inspections are often needed. Manufacturers are using in-process inspection to maintain and control production so as to achieve the desired quality. Inspections have also been considered together with process planning. An integrated process planning and inspection system has been developed (Zhao et al. 2008). On-Machine Inspection (OMI) or On-Machine Measurement (OMM) is considered as one of the effective ways to provide real-time, online inspection for quality control purposes.

However, inspections are mostly a reactive type of quality control. To enable active quality control, machining parameters are best monitored and controlled during machining process, which enables the machine tool behaviour to be analyzed and appropriate actions to be taken in due course. The main consideration of monitoring and control of on-going processes is to record some relevant sensory data so that machine tool characteristics can be understood and fed back for a real-time reaction. Li et al. (2004) concluded that machining processes monitoring and control by optimizing the machine parameters such as feed-rate, spindle speed, depth of cut are able to prevent product quality deterioration, maintain dimensional accuracy, and relax machine constraints.

Over the years, many methods have been developed to overcome and avoid machining overload, using either off-line or online analysis of machining processes. Different sensors such as dynamometers, acoustic emission sensors, and accelerometers, in conjunction with various analysis methods such as fast Fourier transform (FFT) and coherence analysis have been used for monitoring machining conditions (Rubio and Teti 2009; Boud and Gindy 2008; Desforges et al. 2004; Chen and Chen 1999; Byrne et al. 1995). Machining parameters that are commonly used for controlling some aspects of the machining processes such as chatter and cutting force, tend to be selected collectively based on the "worst scenario" and controlled by using various control algorithms. For instance, when tool fracture occurs, the control algorithm should be capable of responding and regulating the speed in real-time or possibly shutting down the operation if needed (Chen 2000).

In early days of chatter avoidance research, focus was on detecting and suppressing chatter by optimizing cutting parameters where spindle speed is mainly considered. Chatter suppression has been improved by strengthening speed modulation when the axial depth of cut is beyond the limit of stability (Ismail and Kubica 1995). Soliman and Ismail (1997) designed and implemented a PD-fuzzy logic controller to suppress chatter. In this controller, an indicator named R-value is used to detect chatter. This R-value is calculated from the cutting force components at both low and high frequencies. The authors also overcome the difficulties in implementing spindle speed modulation due to the inertia of the rotating parts. The major difficulty in applying the speed modulation approach is caused by the high momentum of the spindle system. In the industrial environment, in particular in high-speed machining, slight disturbance of the spindle speed may cause severe unbalance of the spindle speed and hence instability which often leads to machine and tool failures.

Later on, feed-rate was often used as the cutting parameter to be optimized. Spindle torque due to machining with various depth of cut can be reduced by optimizing feed-rate using fuzzy control (Liang et al. 2003). Lim and Menq (1997) proposed two advanced strategies of integrated process planning for precise machining of complex surfaces namely a cutting-path-adaptive feed-rate strategy and a control surface strategy. The aims of the strategies were to reduce machining time and maximize feed-rate by cutting along low-force-low-error machining directions, and to minimize machining errors by using a compensated control surface based on the predicted machining errors.

The research work reported in this paper focuses on the data model for feed-rate optimisation based on a cutting force prediction model implemented at the process planning stage, and real-time process control at shop-floor. A knowledge-based evaluation module is also incorporated. A key feature of the system is the use of STEP-NC data model (ISO 14649-10: 2003; ISO 10303-238, 238: 2003), which enables more design information (e.g. geometry, workpiece information and tolerances) to be incorporated both prior to and during machining processes for optimisation purposes. The rest of the paper is organized as follows. Section "Literature survey" provides a succinct literature survey on some cutting force and cutting power related machining optimisation techniques. Some research work on optimisation and process control based on STEP-NC is also summarised in this section. Section "STEP-NC data model" explains the STEP-NC machining features and machining operations that are utilised in the proposed optimisation system which is reported in section "System architecture". Problem definition, optimisation data model and simulation of the system are given details in section "Development of data model for optimization module". Section "Conclusion" concludes the paper.

Literature survey

When it comes to optimisation for machining processes, cutting force is one of the common outputs that are monitored and controlled. There are a host of machining parameters one needs to work with and/or optimise for.

Studies of cutting forces

Excessive cutting forces limit machining capability, machine performance and productivity. Accurately quantifying cutting force is the first step to an effective control of the machining process. Although several force measurement devices have been used for monitoring and controlling the cutting force, there is a need to obtain the cutting force information during the planning stages of a machining operation (Xu 2009). In other words, a reliable cutting force prediction is desirable in the planning process for determining an optimal speed, feed-rate, and depth of cut.

Feed-rate determination based on the cutting-force model was studied by a number of researchers (Kim et al. 2006; Lee and Cho 2007). The magnitude and profile of cutting force have been precisely predicted with accuracy as high as 95% for general NC machining using the developed geometric cutter model and cutting force model (Kim et al. 2006). Others have determined feed-rates based on the appropriate reference cutting force calculated by a finite element analysis, and considering the transverse rupture strength of the tool material and the area of the rupture surface (Lee and Cho 2007).

A new model of cutting force based on a mechanistic approach was applied at the CAM stage for high-speed milling (HSM) (Lamikiz et al. 2005). The model was applicable in die and mould machining with ball-end mills, and in flank machining of inclined surfaces with end mills. The calculation was accounted for machined spherical geometry as well as the machined surface slope. Estimation of cutting force has also been integrated as a utility function in commercial CAM software to the best selection of the tool-paths for high speed machining of complex surfaces. Cutting forces measured from the experiments were compared with those predicted by the model. The results were verified for different slopes, cutting strategies and cutting parameters.

Research has also been carried out to develop an adaptive cutting-power prediction model for a CAD/CAM system. Chang and Chen (1999) presented a fuzzy-net based, on-line cutting power recognisor for milling operations. Predicted cutting powers were obtained by three approaches, (1) a theoretical model, (2) a theory and fuzzy-net model, and (3) an experiment and fuzzy-net model. The result showed that the cutting power calculated by the fuzzy-net system is more accurate than the power calculated by the formula.

Smithey et al. (2001) presented an enhanced model for the estimation of the shear flow stress and shear angle using a combined slip-line field/mechanistic model approach to cutting force prediction in metal cutting. The new model was then integrated with Waldorf's model to predict cutting forces of a worn tool, thereby establishing a prediction method for force prediction of a worn tool.

Simulation is another way to predict excessive cutting force and optimize cutting parameters. An off-line feed-rate optimisation system based on cutting force simulation was introduced by Zhang (2009). The results showed two comparisons of parameters behaviour for oil-bottle mold semi-finish and finish machining: (1) the number of tool move per time versus maximum cutting force, and (2) the number of tool move per time versus feed-rate. The author concluded that machining time and quality could be achieved by controlling the cutting force.

Optimisation of machining parameters

Optimisation of machining parameters has been deal with in different ways, e.g. graphical-based and mathematical modelling. Graphical-based optimisation tries to optimize cutting parameters based on constraint characteristics (Li et al.

2004; Sencer et al. 2008). The curve of the desired function along the cutter path that may have a significant peak and trough is optimized under the constraint of feed-rate changes. Sencer et al. (2008) showed that the machining time can be significantly reduced by optimizing the feed-rate along the tool-path. The purpose is to find the most optimal feed along the tool-path in order to ensure a smooth and linear operation of the servo drives with minimal tracking errors. On the other hand, feed-rate is optimized based on the curve of cutting force prediction constraint characteristics (Li et al. 2004). The optimisation is done for segment or micro-segment together by using Heuristic methods so that the effective optimisation can be significant while various practical constraints are met.

Optimized machining time and cost, feed-rate, depth of cut, and spindle speed have been described by means of mathematical expression models (Henriques 2006; Satishkumar et al. 2006; Zhang et al. 2006). The optimisation problem of cutting parameters is mathematically defined as an objective function to be maximized or minimized considering any constraint variables to be solved by various techniques. The techniques have been summarized by Aggarwal and Singh (2005). There are two groups of techniques—conventional techniques and contemporary techniques. The conventional techniques include geometric programming, geometric plus linear programming, goal programming, sequential unconstrained minimization technique, and dynamic programming. The contemporary techniques are those of fuzzy logic, scatter search technique, generic algorithm, Taguchi technique, and response surface methodology. Recently, Krimpenis and Vosniakos (2009) applied the technique of generic algorithm to achieve optimisation of rough milling for a part with sculptured surfaces. Three rough milling objectives were considered such as minimum machining time, maximum removed material and maximum uniformity of the remaining volume at the end of roughing.

Process control based on STEP-NC data models

Today's computer numerical controls (CNCs) still employ G-codes that deprive machining processes of much needed information such as workpiece characteristics, tool properties and optimized cutting parameters obtained from a computer aided process planning (CAPP) system. The STEP-NC data models provide the opportunity for CNCs to be provided with the above-mentioned data. This way, higher-level data is conveyed to CNCs. The data model also supports feedback of the process data from servo drives to CNCs and CAPP systems (Wosnik et al. 2006).

Implementing higher-level data provided by STEP-NC, we can control the process purposely and provide the necessary feedback to compensate various types of errors such as static and dynamic errors (Kumar et al. 2007). There are three types of process control feedback, corresponding to three types of errors, i.e. static errors, dimensional errors and surface roughness errors. The first type of process control feedback is related to compensation for the inherent inaccuracies in a machine tool. The second type is to compensate tool's offsets or tolerances in the product information for the dimensional inaccuracy. The third type is for improving surface roughness.

Challenges in the development of data models for machining optimisation

Most of the optimisation results are embedded in machine control data such as G-codes (known as ISO 6983 or RS274D) which drive a machine tool. The G-code format defines a set of low-level data that are mostly step-by-step instructions for a machine tool. Information such as features, tolerances, surface finish and materials is not documented in a G-code file. G-codes therefore are considered as a bottleneck for a complete and real-time optimisation for machining processes. The newly developed STEP-NC (STandard for the Exchange of Product data for Numerical Control) provides an opportunity for such optimisation. This is due to the fact that STEP-NC overcomes the shortcomings of ISO 6983 by providing a comprehensive data model that includes much of the design and manufacturing data. It provides the basis for a bi- or multi-directional data exchange between CAD and CAM systems. To be more specific, STEP-NC programs retain high-level data such as machining features and associated process parameters using the object-oriented concept of Workingsteps. Such a task could be for example rough machining of a pocket or finishing a hole. Through a sequence of manufacturing tasks, all operations necessary to produce the finished part from the raw piece can be described. Clearly, this new data model contains "what-to-do" information, instead of "how to do" information.

In comparison to STEP-NC, ISO 6983 documents mainly axis movements, rather than the machining tasks with respect to the part. The program also supplies the shop-floor with fixed, low-level information such as the cutting parameters, in particular, feed-rate. It is widely recognized that feed-rate optimisation is an effective way of improving and obtaining better machining processes. The rigid data format of ISO 6983 makes feed-rate optimisation difficult because the control will normally just execute the code with a fixed feed-rate (Xu 2009). Conversely, with an optimisation schema developed to work alongside STEP-NC data models, optimisation can be carried out in a more timely fashion to give an optimum feed-rate for a particular duration of machining process. It is possible that the desired feed-rate is attained by considering and verifying the optimized feed-rate under actual machining conditions. Any modifications to the machining parameters at the shop-floor can be recorded, evaluated, and transferred back to the planning phase for a better exchange, and preservation of knowledge and experience.

With the aim of improving machining operations, this paper presents the developed data model for generic feed-rate optimisation based on STEP-NC. The system architecture is also conceived and it consists of STEP-NC complaint optimisation, process control and knowledge-based evaluation. This architecture overcomes a range of problems faced by the systems that are based on G-code.

STEP-NC data model

The STEP-NC data model provides standard data requirements for machining processes associated with CNC machining. The STEP-NC standard is an extension of STEP and allows for connections between STEP-based CAx and CNC. The data models of the STEP and STEP-NC standards are constructed based on the EXPRESS language (ISO 10303-11: 1994). The EXPRESS language is a formal language for the definition of entity-attribute data models. Given that EXPRESS language does not define any implementation methods for building product exchange models, STEP part 21 is the first implementation method that defines the basic rules of storing EXPRESS/STEP data in a character-based physical file (ISO 10303-21: 1994).

STEP-NC data file

The data section of a STEP-NC file has three sub-sections, a Project entity, Workplan/executables and Geometric description. The data in a STEP-NC file consists of instances of entities. One of the instances is called Workplan which contains sequenced subsets of executable manufacturing tasks or commands and may also include information of workpiece to be machined (ISO 14649-10: 2003; ISO 14649-11: 2003). The executables can be of three different types: Workingsteps, NC functions, and program Structures. *Machining_workingsteps* are the essential elements of *executables* in a STEP-NC physical file, which are defined based on *two5D_manufacturing _feature* and 3-D (region) of *machining_features*. They therefore specify the connection between a distinct manufacturing feature and a machining operation to be performed on that feature. Each Workingstep also includes further sub-features such as *planar_face*, *pocket*, *step*, *slot* and *round_hole*, in addition to cutting condition information. The Workplan combines several executables in a linear order or depending on given conditions if conditional controls are used. Some geometrical data information for workpiece, set-ups, manufacturing features, machining strategy, tooling etc. is also included in a STEP-NC physical file. Figure 1 shows part of the internal structure of STEP-NC data.

Machining features

Since the research reported herein utilises the definitions of machining features in the STEP-NC standard, it is necessary to analyse the taxonomy of the STEP-NC features. In STEP-NC, machining feature is placed in an object-oriented data structure as shown in Fig. 2. *Machining_features* as the supertype of all features and the subtype of *two5D_machining_feature* are defined in close resemblance to ISO 10303-224 (ISO 13030-224: 2001). They include *planar_face*,*pocket*,*slot*,*step*, and etc. Their definition, entity and attribute are explained in ISO 14649-10: 2003 standard. A feature is described as a form of machining contour that consists of a set of parameters. For instance, *planar_face* is described as machining of the outer of a workpiece. Two attributes are used to define *planar_face* includes *course of travel* and *removal boundary*. *Course of travel* denotes a straight-line with magnitude and direction, whereas *removal boundary* denotes a line with direction and magnitude that when swept along a path defines the area on a workpiece for volume removal. The geometry of the *planar_face* in *z*-axis is given through the depth. The depth expresses the bottom of the material that needs to be taken away from the workpiece to reach the final shape of the feature.

Unlike *planar_face*, *step* has only one defined attribute, i.e., *open boundary*. *Open boundary* denotes the outline or shape that forms the upper edge of the *step*. When travelling along the curve as defined by its sense, the material is to the left of the curve. However, both *planar_face* and *step* inherit depth as an elementary surface which can be inclined or orthogonal to the feature's local z-axis.

Pocket is a supertype of *closed_pocket* and *open_pocket*. A *closed_pocket* is a pocket with its feature boundary given by its contour on the outer face that is enclosed by the workpiece and its depth. Unlike *closed_pocket*, *open_pocket* is a pocket with its feature boundary given by an *open_boundary* and a *wall_contour*. *Open_boundary* denotes the outline or shape that forms the upper edge of the *open_pocket*, and *wall_contour* denotes the outline or shape that forms the side-edge of the *open_pocket*. The contour is defined implicitly by the selected tool and the fillet options inherited from *machining_feature*.

Similar to pocket, entity *slot* also has two types – *slot* with radiused end and *slot* with two open ends. Generally speaking, a *slot* is a special type of pocket. Entity *slot* consists of only one attribute, i.e., *Course_of_travel*. *Course_of_travel* denotes the location and extension of the slot. *Slot* is typically machined by a single remove, whose shape is given by the tool's diameter. However, when a *slot* has a bigger width than the tool's diameter, more than one cut will have to be made. The complete description of *planar_face*, *step*, *closed_pocket*, *open_pocket*, *slot* can be seen in Fig. 2a, b, c, d and e, respectively.

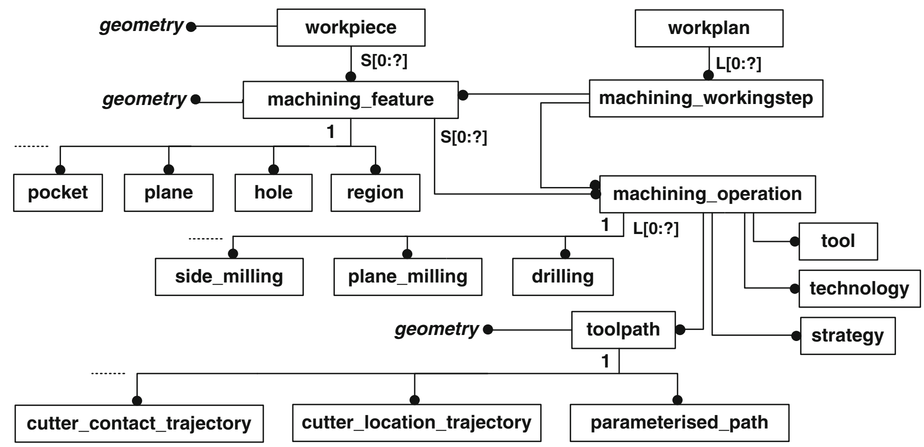

Fig. 1 Geometry, technology and process information in STEP-NC (2000)

Milling data represented in a STEP-NC model

In addition to the machining feature information, STEP-NC data model also captures information about machining operations. For example, process data for milling is represented in ISO 14649-11: 2003, specifying the technology-specific data element needed for defining milling processes. Among various types of data, *milling_type_operation* is utilised in this research and is therefore discussed in this section.

Milling_type_operation is inherited from entity *machining_operation* defined in ISO 14649-10 to describe machining technology and strategy. Meanwhile, *milling_type_operation* is also a supertype of *freeform_operation*, *two5D_milling_operation*. A few *two5D_milling_strategies* are used in the proposed systems, i.e. *unidirectional*, *bidirectiona*l, *contour_parallel*, *bidirectional_contour*, *contour_bidirectional*, *contour_spiral*, *center_milling* and *explicit_strategy*. Optional information of *overlap* is required for machining strategy in the proposed system. The overlap is the path between two neighbouring cutting movements as percentage of the tool diameter. In a latter section, the overlap is categorized as either full-immersion or part-immersion.

System architecture

This section discusses the proposed system architecture. The system architecture can be separated into three subsystems (Fig. 3).

The first subsystem is the Optimisation Module, responsible for optimizing feed-rate which is calculated based on the information concerning machine tool capability. Later, the developed Optimisation Module is used to perform the data model. This is the main focus of this paper. The maximum allowable depth of cut and allowable motor drive power are taken into account. In order to provide the necessary information for optimisation purposes at the planning stage, the following data are considered,

(1) Machine tool capability in terms of the material removal rate considering machine vibration and allowable cutting forces. The machine tool capability could be retrieved from an existing machine tool database.
(2) Motor drive power and mechanical efficiency.
(3) Type of machining strategy.
(4) Cutting tool information.
(5) Workpiece material properties.

The second subsystem is the process control module responsible for process control to maintain a feed-rate with a desired set-point and to generate feed-rate to update the machining conditions. In order to provide the necessary information for process control in real-time, the following data are considered,

(1) Set-point regulation signal for the appropriate drive signals of machine tool's axis (synchronize signal input).
(2) Sensor placement for appropriate axis movement in acquiring data signal.
(3) Proper sampling frequency which is synchronized with other concerned equipment.
(4) Cutting force threshold.
(5) Appropriate control action algorithm.

The third subsystem is the Knowledge Based Evaluation (KBE) module, responsible for recording and evaluating updated data information at shop-floor. Four parameters, namely surface quality, machining time, actual cutting force and actual feed-rate, are evaluated to make sure that the allowable cutting power of machine tool is not exceeded. This information is used for updating the data in the STEP-NC data model.

Optimisation module

The aim of this subsystem is to optimize feed-rate. The calculation is based on the information about machine tool's

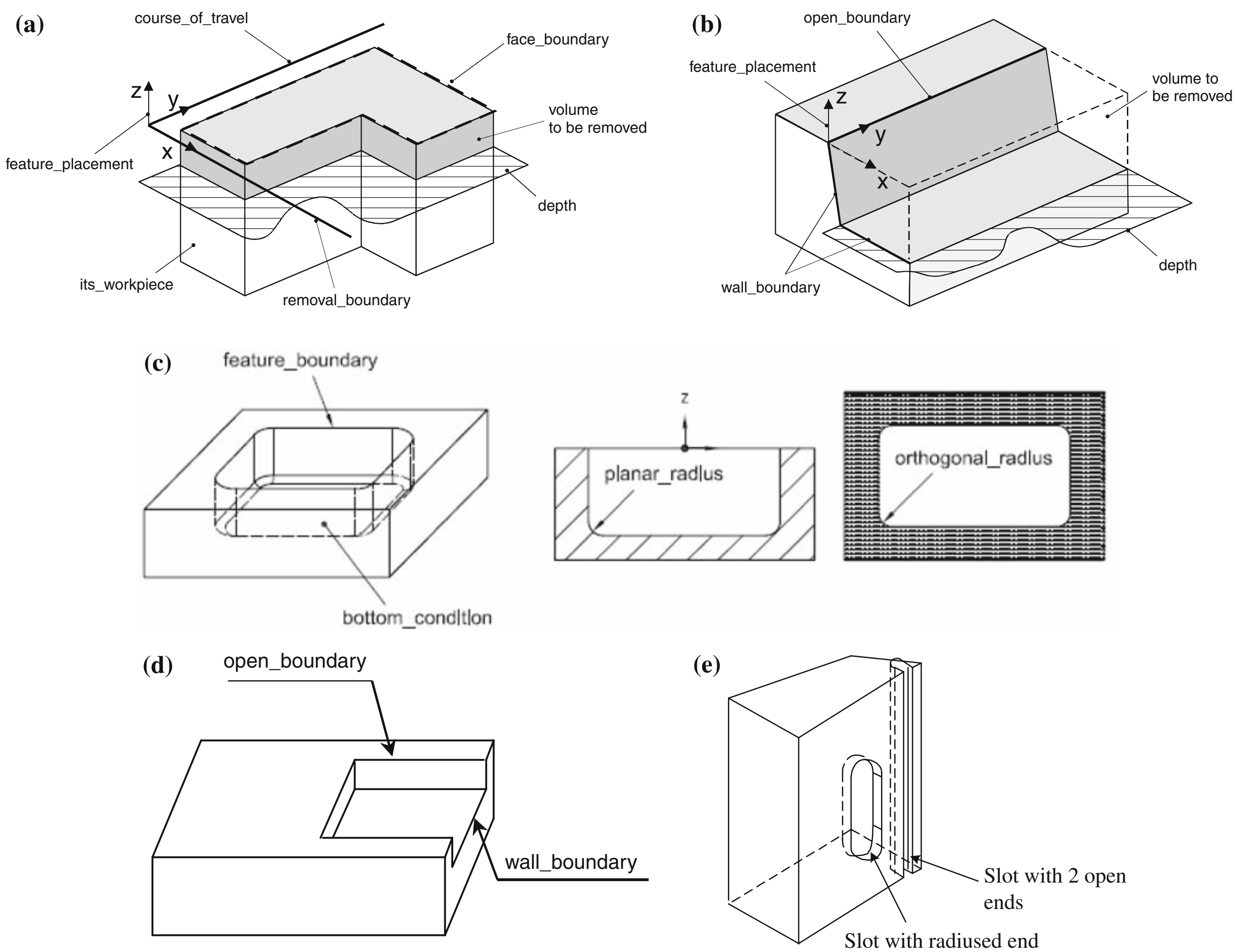

Fig. 2 Some STEP-NC features

capability. The optimal feed-rate is then integrated into process planning. Figure 4 illustrates the IDEF0 diagram of the first subsystem. In general, the system utilizes the AP-203 or AP-214 data to bring the geometry into the system, which is then converted into manufacturing features defined in the AP-224 format. It is this manufacturing feature information that is used by the Process Planning module. The module contains the STEP-NC data modelling schemas for machining operations defined by ISO 14649 Part 10:2003, Part 11:2003 and Part 111:2001.

Interpreter is the first module in this subsystem. It takes STEP Part 21 files (ISO 10303-21: 1994) as input. These files contain the information about design, process planning and manufacturing, conforming to ISO 10303 AP203 and AP-214. The information is then converted to manufacturing features conforming to the STEP-NC standards. This feature information is input to the Process Planning module.

Proper feed-rates for different machining operation(s) are determined by the Optimisation module. Optimisation module is about the optimizing the feed-rate for a particular machining feature. It is specified in entity *cutting_force*. The aim of the Optimisation is to re-use the cutting force information specified to calculate the feed-rates to be used to machine all features. Generic feed-rate is arranged by the optimisation procedure, which is explained in section "Process monitoring and control". Type of machining, cutting strategy, optimizing algorithm, machine capability data information and additional data information from the workpiece and tool are involved in the Optimisation module.

The aim of the process planning stage (Fig. 4) is to enrich machining features represented in AP-224 with the necessary syntax information to form entities defined by STEP-NC. This contains "what-to-do" information instead of "how-to-do" information. The "what-to-do" information maintains its generic nature until the last moment when a

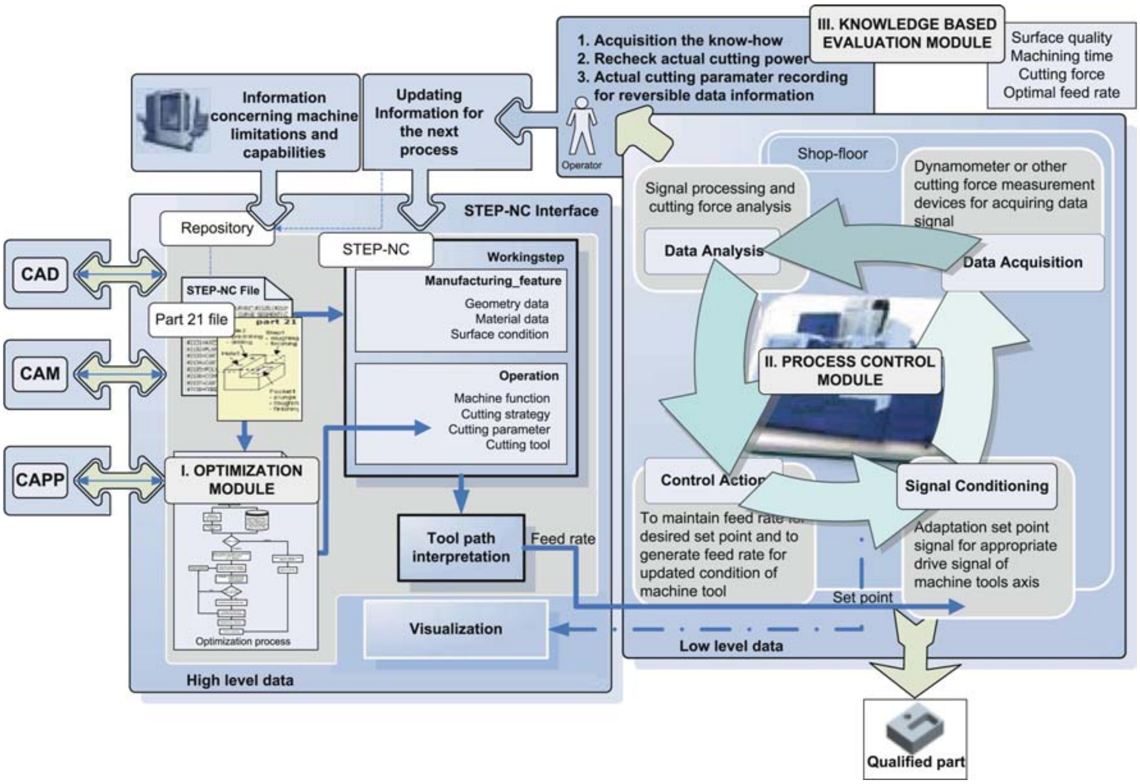

Fig. 3 Proposed system framework

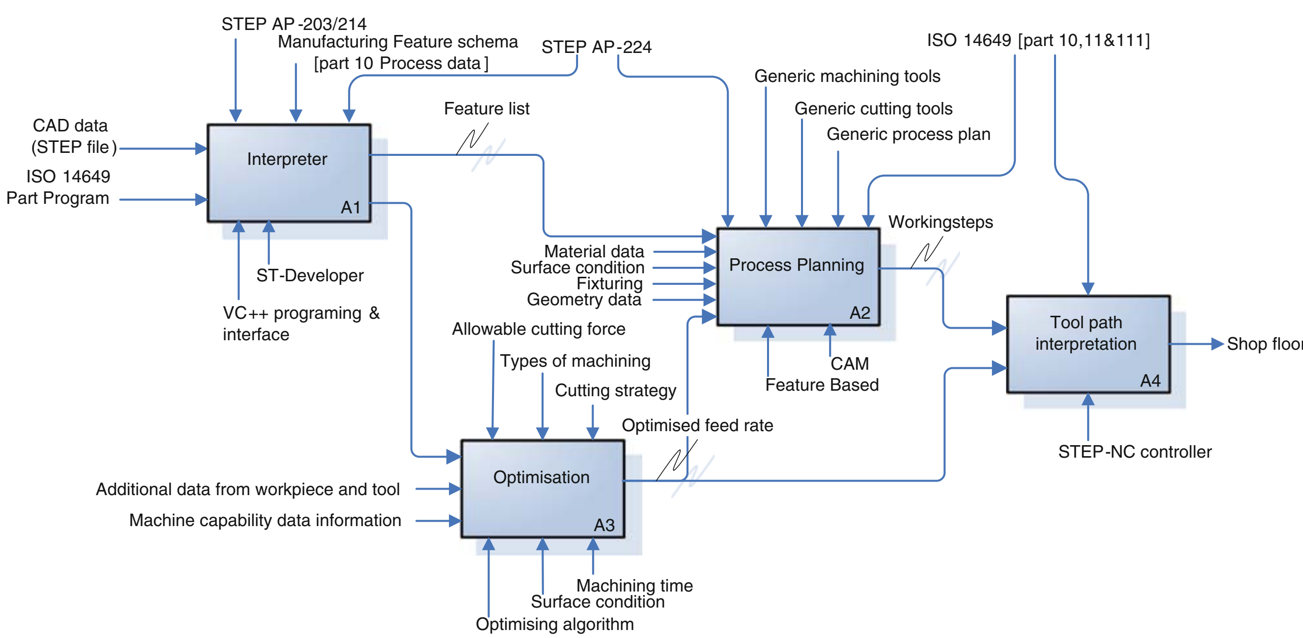

Fig. 4 IDEF0 diagram for detailed design of optimisation module

CAM system populates the process plan with native manufacturing information in order to generate a specific "how-to-do" process plan (Wang et al. 2007; Xu et al. 2006; Xu 2009; Kramer et al. 2006). Generic machining tools and generic cutting tools conform to the data defined by ISO 14649 Part 111 (ISO 14649-111: 2001). The data generated by the modules is mapped into the Tool Path Interpretation module. This module generates Canonical Machining Commands (CMC) (Proctor et al. 1997), or other type of machine control data. Canonical Machining

Commands is a specific set of commands for machining operation. STEP-NC controller is responsible for executing the STEP-NC data at the shop-floor.

Process monitoring and control

The second module of the proposed system is the Process Control module. The main function of this module is in fact process monitoring and control. There are four main stages in the module (Fig. 5). In stage one, machining takes place with given signals of a set-point. The set-point signals are the signals generated by a STEP-NC controller. In order to synchronize the set-point signal suited for the actuators of the machine tool, signal conditioning is used.

During the second stage, cutting force signals of the machining process are acquired using a dynamometer. These signals represent the cutting forces that can infer phenomenon such as tool wear, tool breakage, machine performance, surface conditions, heavy burr, dimensional errors and tool temperature. The output of the acquired data is a time-domain data signal.

In stage three, the time-domain signals are processed using a signal processing algorithm so as to understand the behaviour of the machine tool. Several methods of signal processing methods can be utilized to analyze the onset of cutting forces. Monitoring the onset of cutting forces can be done since the threshold of cutting forces has been determined. The output of this stage is to produce a warning signal in lieu of cutting force abnormality, which is then used for control algorithm.

Stage fourth involves a control action process, which contains a procedure of real-time feedback action for an adjusted feed-rate signal at a cutting force warning signal. The concept of the real-time feedback loop is to control the dynamic behaviour of the system by means of subtraction of the sensed signal from the set-point signal to create the error signal that is amplified by the controller. The controller manipulates the inputs to the machine actuators based on the error signal to obtain the desired signal. The output is the desired actual feed-rate.

Knowledge-based evaluation

The last action in the system is to record the actual feed-rate as part of the knowledge-based evaluation process. This entails evaluating the recently recorded cutting forces, feed-rate, machining time and surface quality for subsequent machining processes. This information is used to update STEP-NC data. Table 1 shows the type of data used for evaluation.

Development of data model for optimisation module

To incorperate STEP-NC data for dynamic planning of cutting parameters, a data model for optimisation is needed. Such a data model integrated in STEP-NC has not been developed. This data model should be generic enough to include all data used for optimisation which is needed for different machining operations. Therefore, problem formulation and procedure for optimisation is defined to support the data model. To verify the algorithm, a simulation tool has been developed. A case study is then performed to simulate several conditions where different types of cutting parameters are assigned. Finally, the data model for optimisation based on STEP-NC is developed.

Problem definition

The main objective of this research is to advise a maximum possible feed-rate for different machine tools by considering machine tool capabilities. Each machine tool has its own power rating. Considering machine tool's nominal power, a maximum feed-rate for time-critical milling is calculated with cutting force as the main constraint. The cutting power is determined based on mechanical efficiency and is kept below the main drive motor power. The depth of cut is selected based on the machining allowance. In the case of quality-critical operations whereby a smaller depth of cut is used, a feed-rate is chosen considering requirements such as surface quality. In both situations, the cutter capability in terms of maximum feed per tooth is another constraint considered.

In this work, the mathematical model of cutting force for milling proposed by El-Hofy (2007) is adopted. It is mainly used for face milling operations. Different types of face milling operations are classified and dealt with (Fig. 6). Full-immersion machining (Fig. 6a) is a milling operation when the radial width of cut equates the milling cutter diameter. Part-immersion machining (Fig. 6b, c) occurs when the radial width of cut is smaller than the milling cutter diameter. Two types of part-immersion milling can occur. If a cutter is only engaged in milling on one side, it is called unidirectional-immersion. If the middle part of the cutter is engaged in milling, it is called bidirectional-immersion.

Optimisation problem is carried out for two different scenarios: (a) maximizing feed-rate and minimum machining time for time-critical (TC) machining operations and (b) optimum feed-rate for quality-critical (QC) machining operations. In most cases, TC machining operations are referred to roughing operations whereby increasing the material removal rate is one of the main goals and cutting power is the main constraint. On the other hands, QC machining operations are often for finishing purposes whereby surface quality is the main concern but cutting power is not.

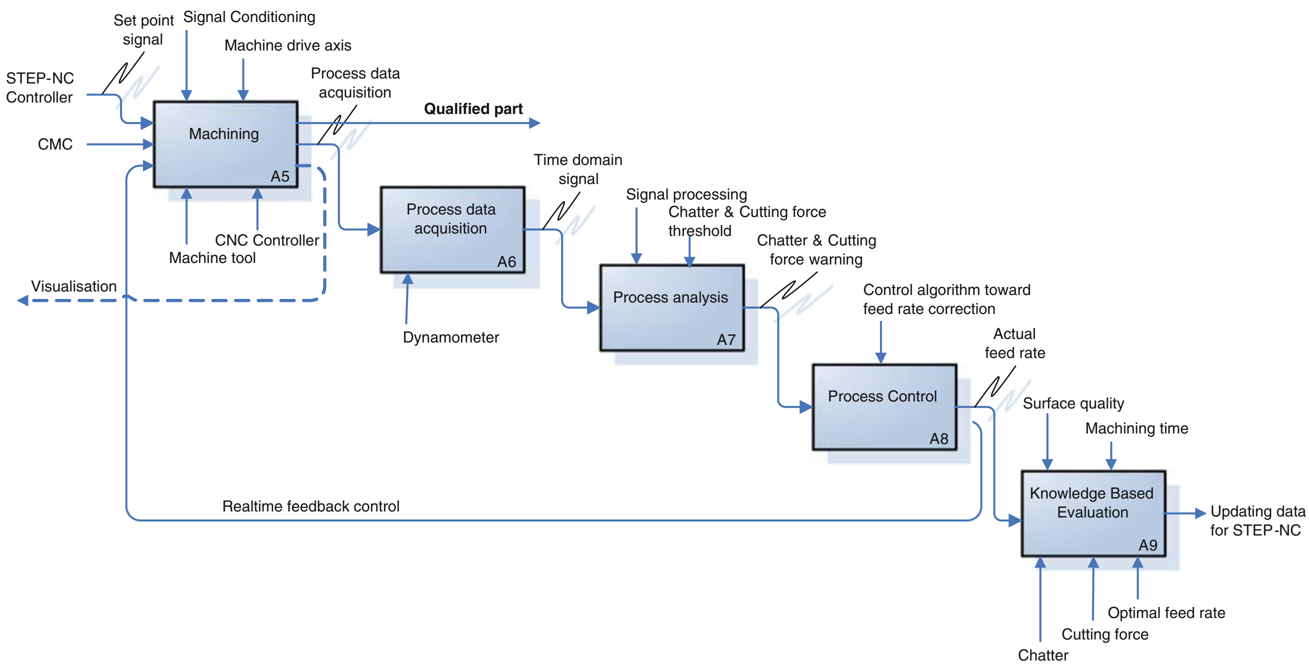

Fig. 5 IDEF0 diagram for the detailed design of process control

Table 1 Output of data evaluation

Machine_ID	Feature_ID	Geometrical data			Workpiece material		Cutting tool		Feed per tooth (mm/rev)				Cutting	
									Roughing (f_z)		Finishing		Type	Strategy
		L/X	a_t	a_s	ID	k_c	ID	V_c	Predicted	Evaluated	f_z	a_s		
Machine tool_ID	Slot_2	150/100	20	3	ST37	1,000		35	0.4	0.33	0.1	1.5	d_{s1}	1
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Machine tool_B	Pocket_1	120/150	–	–	–	–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Machine tool_C														

The governing equations

Take bidirectional-immersion as an example (Fig. 7), the mean chip thickness can be expressed as,

$$h_{m(\chi)} = \frac{f_z \sin\chi(\cos\varphi_1 - \cos\varphi_2)}{\overline{\varphi_c}}(\mathrm{mm}) \quad (1)$$

where,

f_z = feed per tooth (mm/r)
χ = setting angle (deg)
φ_1 = entrance angle (deg)
φ_2 = exit angle (deg)
$\overline{\varphi}_c$ = contact angle in horizontal milling (radians)

Feed-rate can be calculated by

$$f_s = f_z n Z_c(\mathrm{mm/min}) \quad (2)$$

where,

f_z = feed per tooth (mm/r)
n = cutter rotational speed (rpm)
Z_c = number of cutting teeth

Cutting speed can be calculated by

$$V_c = \frac{\pi dn}{1000}(\mathrm{m/min}) \quad (3)$$

where, d= tool diameter (mm).

Thus, the total mean cutting force F_{mt} (in the direction of the cutting speed V_c) becomes,

$$F_{mt} = \frac{k_s f_s a_s(\cos\varphi_1 - \cos\varphi_2)}{2\pi.n}(\mathrm{N}) \quad (4)$$

where,

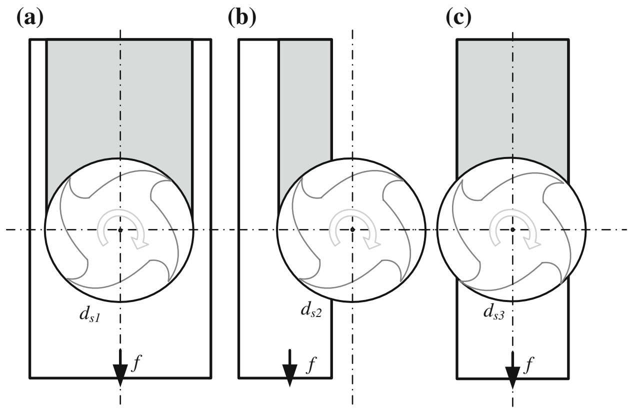

Fig. 6 Different types of face milling

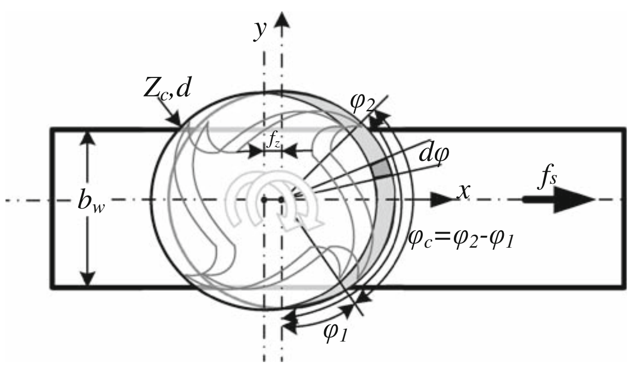

Fig. 7 Chip parameters in face milling

$k_s =$ specific cutting resistance (N/mm^2)
$f_s =$ feed-rate (mm/min)
$a_s =$ depth of cut (mm)

The main cutting power, N_c can be calculated as

$$N_c = \frac{F_{mt} V_c}{60 \times 10^3} \text{ (kW)} \tag{5}$$

where, $F_{mt} =$ total mean tangential milling force.

If η_m is the mechanical efficiency, the motor power, N_{mc} can be expressed as

$$N_{mc} = \frac{N_c}{\eta_m} \text{ (kW)} \tag{6}$$

The feed-rate is subject to hard constraints that satisfy

$$f_{\min} \leq f_s \leq f_{\max} \tag{7}$$

The cutting depth is bounded by the upper and lower limits

$$a_{\min} \leq a_s \leq a_{\max} \tag{8}$$

The peak to valley surface roughness, R_t, and the arithmetic average roughness, R_a, can be estimated theoretically from (El-Hofy 2007)

$$R_t = \frac{f_s^2}{8r_t} (\mu\text{m}) \tag{9}$$

where,

$r_t =$ tool nose radius (mm)
$R_t =$ peak-to-valley surface roughness (μm)

$$R_a = \frac{f_s^2}{18\sqrt{3r_t}} \text{ } (\mu\text{m}) \tag{10}$$

where, $R_a =$ arithmetic surface roughness (μm).

Machining time is calculated by

$$t_m = \frac{l_m}{f_z z_c n} (\text{ min}) \tag{11}$$

where, $l_m =$ total travel at whole feature path (mm)

Time-critical optimisation

For TC machining operations, we have

$$f_{s1}^{\text{opt}} = \text{Max}\, f_z \left(f_{\max} \leq (8r_t R_a)^{1/2}, a_{\max}, x(t) \right) \tag{12}$$

$$t_{s1}^{\text{opt}} = \text{Min}\, t_m \left(f_{s1}^{\text{opt}}, a_{\max}, d_{si} \right) \tag{13}$$

where,

$x(t) = (N_m, n, k_s, V_c, t)$
$N_m =$ main drive motor power (kW)
$f_{s1}^{\text{opt}} =$ optimum feed-rate (mm/min)
$t_{s1}^{\text{opt}} =$ optimum machining time (min)
$a_{\max} =$ maximum depth of cut (mm)
$d_{si} =$ different types of face-milling
$d_{s1} =$ full-face milling type
$d_{s2} =$ unidirectional part-face type
$d_{s3} =$ bilateral part-face type

The following constraints are considered:

(1) Depth of cut constraint: $a_s \leq a_{\text{allowable}}$, where $a_{\text{allowable}}$ depends on milling machine capability
(2) Types of face milling: d_{s1}, d_{s2} and d_{s3}
(3) Selection of V_c based on cutting tool properties (e.g. HSS, Carbides, or Ceramics and its constraint factor if any)
(4) Cutting force constraint: $F_{mt} \leq F_{\text{mtallowable}}$
(5) Machine's motor power: $N_m \leq N_{mc}$ (Motor power has to be larger than the predicted motor power)
(6) Feed mechanism constraint: $f_{mz} \geq f_{s1}^{\text{opt}}$

Quality-critical optimisation

For QC machining operations, we use

$$f_{s2}^{\text{opt}} = \text{Min}\, f_z \left(f_{\min} \geq (8r_t R_a)^{1/2}, a_{\min} \right) \tag{14}$$

where, f_{s2}^{opt}= Optimum feed-rate (mm/min)
The following constraints are considered:

1. Depth of cut: $a_{\min} \leq a_s$
2. Arithmetic surface roughness is taken into account rather than the feed-rate: Min $R_a \leq \overline{R_a}$

Optimisation procedure

As mentioned before, optimisation is carried out for two different scenarios: (a) maximizing feed-rate and depth of cut for TC machining operations and (b) maximizing surface quality for QC machining operations. Figure 8 shows the optimisation procedure. The maximum depth of cut for TC machining can be obtained from the machine tool capability database.

The optimisation procedure consists of the following steps (see also the corresponding numbers in Fig. 8).

Step 1: "Feature-ID" is selected and its dimensions are obtained.
Step 2: Motor power for a specified machine tool and maximum allowable depth of cut are obtained from the database.
Step 3: Machining information such as mechanical efficiency, motor power, cutting speed, workpiece properties, tool geometry and number of teeth are set.
Step 4: Machining types are determined.
Step 5: Optimisation for TC operation starts with selecting the initial maximum depth of cut.
Step 6: Maximum feed per tooth is selected to start the calculation. The goal of optimisation is to reduce machining time.
Step 7: Calculations for cutting force, cutting power and predicted motor power are carried out.
Step 8: If the predicted motor power is larger than the main drive motor power available, feed per tooth is reduced. Otherwise, the process goes back to step 5.
Step 9: Iteration continues until the predicted motor power is less than the main drive motor power. Feed-rate is then calculated using the final feed per tooth.
Step 10: If the depth of cut is smaller than the allowable depth of cut, the optimisation process ends.
Step 11: Optimisation for QC operations starts. The goal is to achieve required surface quality.
Step 12: The final feed-rate is then used for operation data required in STEP-NC data model.

Computer model and simulation of the optimisation module

A simulation system has been developed to validate the Optimisation module. To simulate the cutting force fluctuation as in a real situation, a random noise of a certain range is added to the theoretical cutting forces that have been calculated. The governing equations of the parameters are incorporated in the case study.

Computer model

The interface has three panes and a window displaying plots (Fig. 9). The input data pane contains information about a milling process such as different types of milling operations, properties of workpiece and tool material, flute number, mechanical efficiency and chip-load. The user has the option to set the required value for these data. In order to calculate the power and cutting force, information such as allowable depth of cut based on machining capability and the main machine power are pre-set.

The machine tool data pane displays information about machine tool capabilities such as machine motor power and maximum depth of cut. The output pane shows the predicted power consumption cutting force, current feed per tooth, current feed-rate and material removal rate as well as the power limit warning indicating the safe limit and over limits of power consumption. This pane also provides two switches such as ON/OFF and TC/QC. ON/OFF switch is used for starting the simulation. TC/QC switch is a switching function between two types: TC and QC that are used for roughing and finishing respectively.

The window displaying plots at the top shows the feed-rate, cutting force and material removal rate, all on the time domain. This is done by calculating the input data of mechanical efficiency, different types of milling process, tool material, workpiece material, tool geometry, maximum feed per tooth depth of cut and machine power. The result from the calculation gives the optimized value of the feed-rate that changes according to the value of the cutting force. For example, if the calculated cutting power is larger than the main machine power, the feed per tooth will be reduced until the calculated cutting power reach an allowable value, i.e. less than the main machine power. By doing this, excessive cutting forces can be avoided.

Optimal results

A case study was performed to simulate several conditions where different types of cutting parameters were assigned. The numbers in the plot of Fig. 9 indicate certain events. Under TC condition, the following changes occur. From 1 to 2, the chip-load increases when small depth of cut is used. However, the cutting force remains constant in order to maintain the power consumption so that it will not exceed the machine power capability. By increasing the machine power, the cutting force, chip-load and MRR decrease simultaneously as shown from point 3 to 4. This decrement will

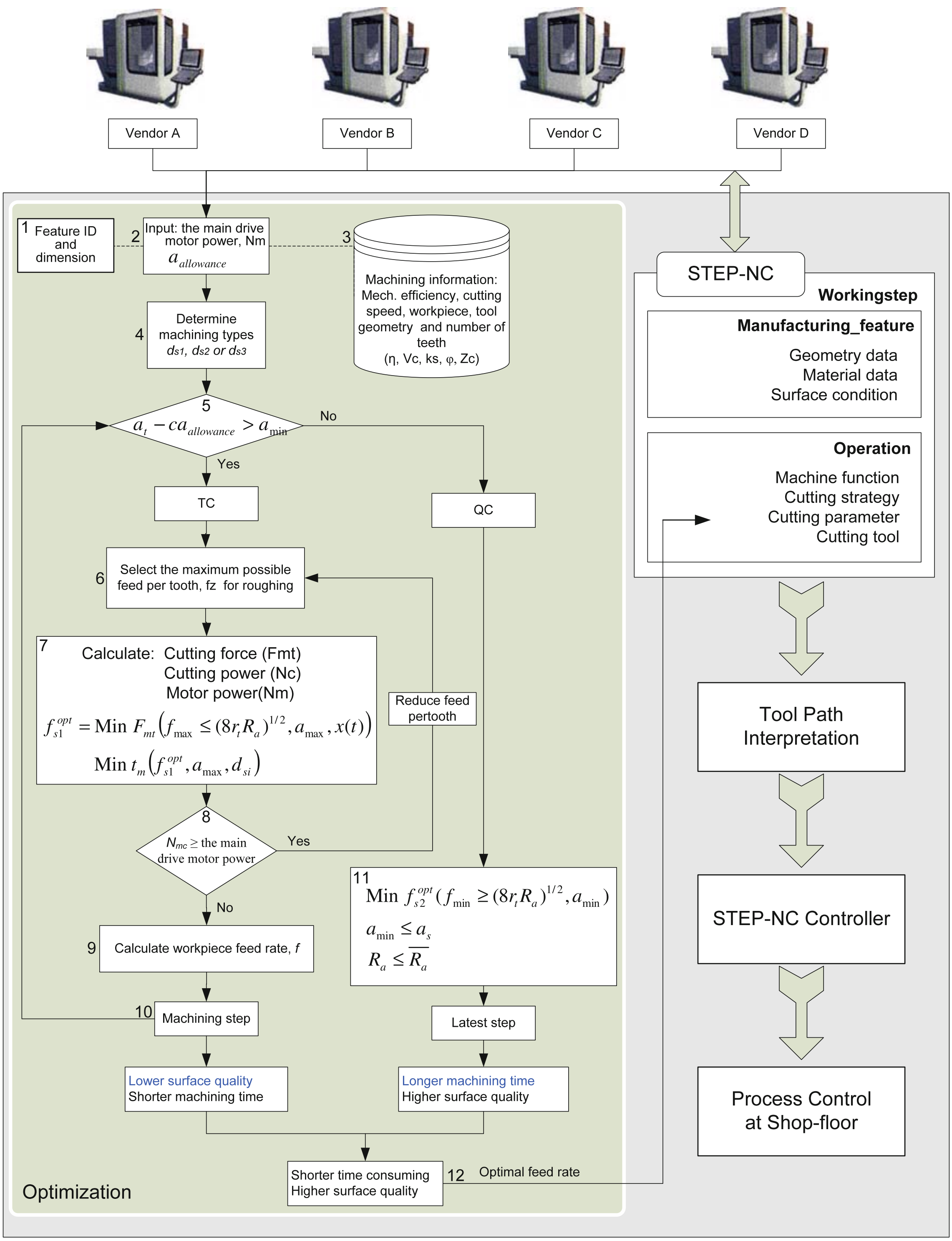

Fig. 8 Optimisation procedure

behave based on the machine power available on the different machine tools. Points 5 and 6 show the effect of different type of workpiece selection to the three parameters shown in the graph. When the workpiece is changed from steel to aluminium, the chip-load and MRR rise. On the other hand, the cutting force again remains constant.

Point 6 is the condition where the operation types switches on QC. Unlike TC, QC is used for quality operation purposes.

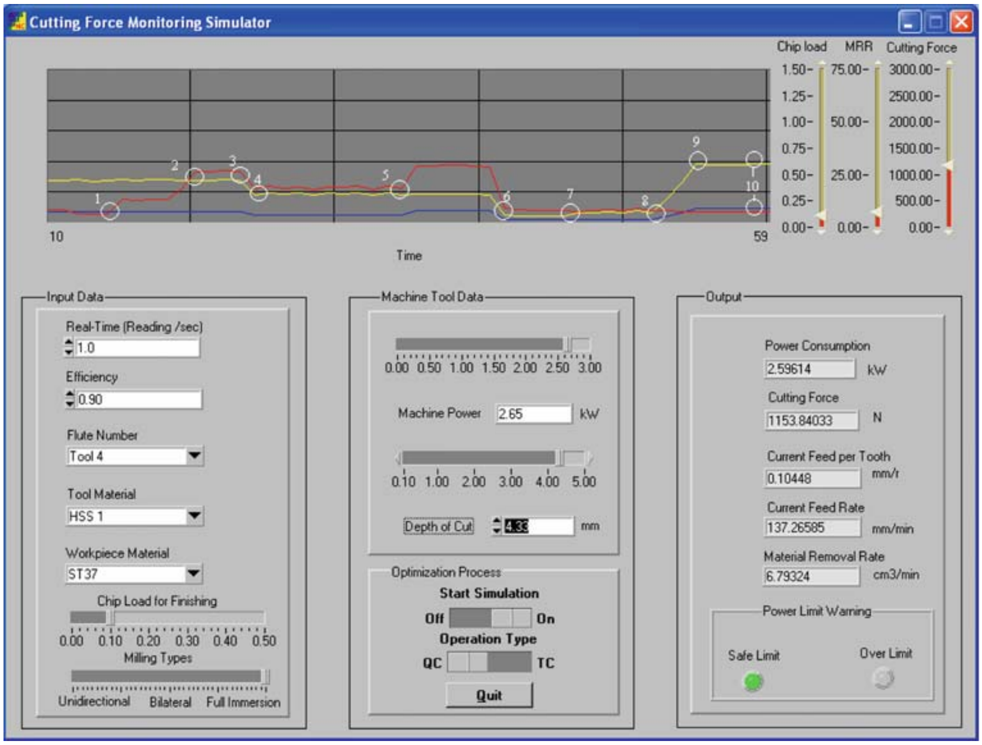

Fig. 9 Monitoring and optimisation simulator

The chip-load is input by the user. In this case, the cutting force slightly increases when the workpiece is changed from aluminium to steel. In this case, chip-load and MRR are remained constant as shown from point 7 to 8. Similarly, the cutting force increases extremely when bigger the depth of cut is used where chip-load and MRR remains constant as shown from point 8 to 9. If there is any change for machine power, it does not influence the graph as shown from point 9 to 10. This is particularly true since the finishing operation is always kept in small chip-load. In addition, Power Limit Warning shows on/off safe limit and over limit. When the power consumption exceeds the machine power, the Over Limit is switched on and vice versa. In the graph, the warning is always kept in Safe Limit. Therefore, the optimisation algorithm effectively adapts to the situation.

Developed data model for optimisation

STEP-NC data model provides standard data requirements for machining processes associated with CNC machining. However, it contains limited information for optimisation. In order for STEP-NC to support machining optimisation, there is a need for a data model to be developed for optimisation and incorporated with the rest of the STEP-NC data model. This section discusses such a data model. Like other STEP schemas, the optimisation data model is also developed using EXPRESS (ISO 10303-11: 1994)—a formal language for the definition of entity-attribute data models in STEP. Figure 10 is the EXPRESS-G diagram of the developed optimisation model.

The optimisation model takes place in one of attributes of *machining_operation* that is defined in ISO 14649 Part 10. The top level of the optimisation model has attributes such as *its_id*, *main_drive_motor_power*, and optionally *process_description*. There are two subtypes under entity *optimisation*: *time_critical_optimisation* and *quality_critical_optimisation*. Entity *time_critical_optimisation* contains data needed for optimising a TC machining operation, e.g. attribute *feed_per_tooth_max* and *axial_cutting_depth_max*.

Entity *power* is supertype of *main_cutting_power* and *machine_power*. Entity power has an attribute which is *its_power_property*. Entity *property_parameter* is supertype of *numeric_paramater* which has two attributes, i.e., *parameter_value* and *its_parameter_name*. Underneath entity *main_cutting_power* are two attributes, *its_cutting_force* and *spindle_speed*. Attribute *cutting_force* is an entity that has *face_milling_type*, *spindle_speed*, *feed_per_tooth, specific_cutting_resistance* and *axial_cutting_depth* as its attributes. Entity *face_milling_type* has two attributes, i.e., *zheta* and *immersion_types*. Unlike *time_critical_optimisation*, the QC operation has *feed_per_tooth* and *axial_cutting_depth* as its attributes.

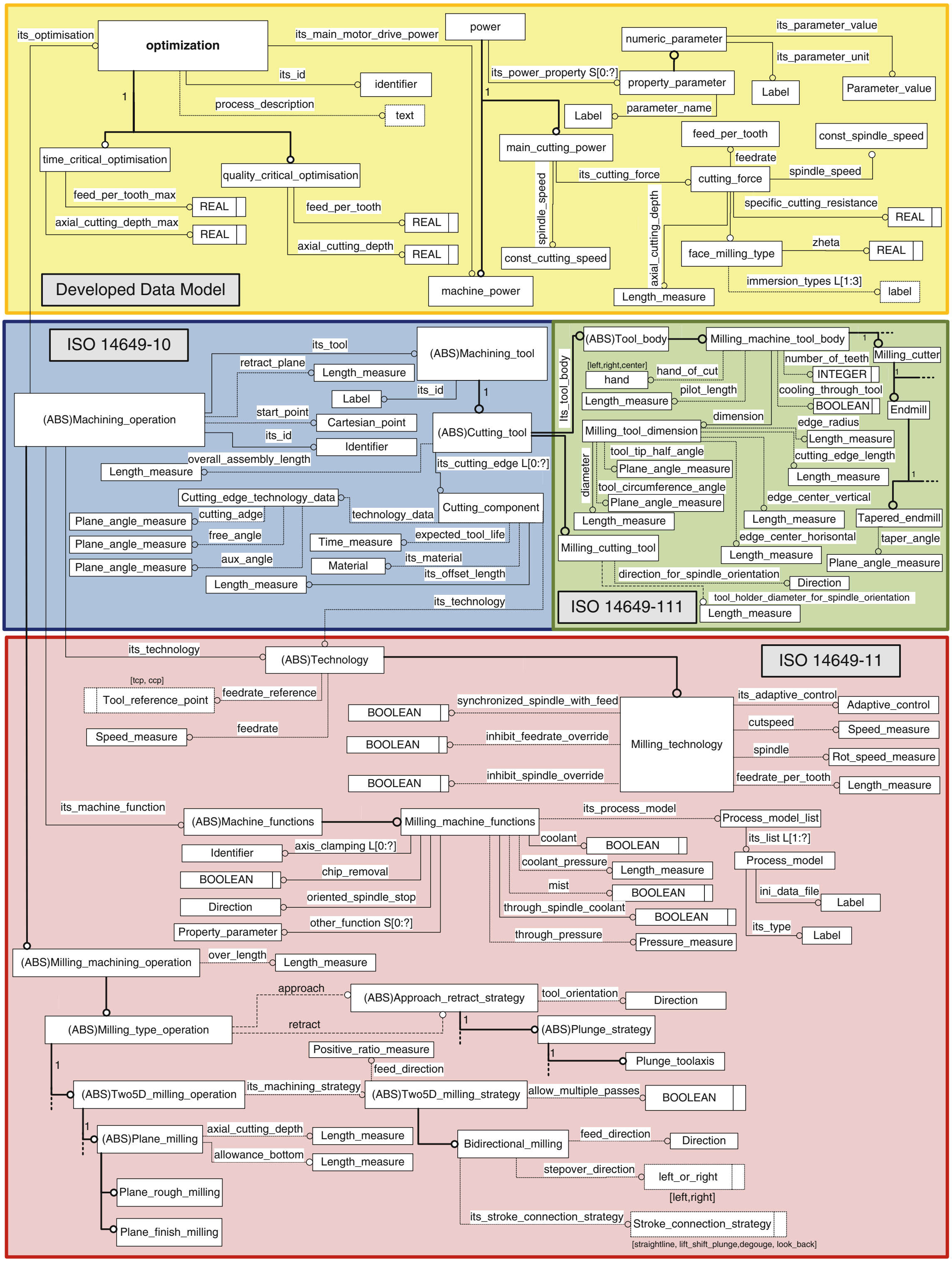

Fig. 10 Optimisation data model

STEP Part 21 file is used to define the basic roles of storing instance optimisation data described in EXPRESS. The data consist of instances of entities that follow the proposed data model of optimisation. One of the instances is called Optimisation which contains the subsets of time_critical_optimisation or quality_critical_optimisation, and their subsets. The instance data of Plane_rough_milling shown in Fig. 11 line #20 was extracted from the current standard in

```
ISO-10303-21;
HEADER;
FILE_DESCRIPTION(' ');
FILE_NAME(' ');
FILE_SCHEMA ((' '));
ENDSEC;
.
.
.

/***************************************************/
/* Instance data extracted from ISO 14649  */
/***************************************************/
#20= PLANE_ROUGH_MILLING ($,$,'ROUGH PLANAR FACE1', 10.000, $, #39, #40, #41, #200,$, #60, #61, #42, 2.500, $);
#39= MILLING_CUTTING_TOOL('MILL 18MM',#29,(#125),80.000,$,$);
      #29= TAPERED_ENDMILL(#30,4,.RIGHT.,.F.,$,$);
      #30= MILLING_TOOL_DIMENSION(18.000, $,$, 29.0, 0.0, $,$);
      #125= CUTTING_COMPONENT(80.000,$,$,$,$);
#40= MILLING_TECHNOLOGY(0.040,.TCP.,$,-12.000,$,.F.,.F.,.F.,$);
#42= BIDIRECTIONAL_MILLING(0.05, .T., #43, .LEFT., $);
      #43= DIRECTION ('STRATEGY PLANAR FACE1: 1.DIRECTION', (0.000, 1.000,  0.000));
#60= PLUNGE_TOOLAXIS($);
#61= PLUNGE_TOOLAXIS($);
/*****************************************************************************/
/*  Instance data extracted from the developed data model for optimisation */
/*****************************************************************************/
#200= TIME_CRITICAL_OPTIMISATION('POCKET MACHINING', #201, 'ROUGHING', 0.5, 3);
#201= MACHINE_POWER('MACHINE POWER',0.29, 'kW');
#202= MAIN_CUTTING_POWER ('CUTTING POWER', $, 'kW', #203, 35)
#203= CUTTING_FORCE (1000, #204, 500, $, 0.5, 5)
#204= FACE_MILLING_TYPE (180.0,"FULL_IMMERSION")
.
.
.
ENDSEC;
END-ISO-10303-21;
```

Fig. 11 Native STEP Part 21

ISO 14649. The instance consists of several attributes. For the proposed instance data, a new attribute was added. This can be represented by #200 as shown in Fig. 11. Detailed clear text coding of the optimisation instance data that corresponds to a Part 21 file is generated by the example of cutting parameters as shown in Table 2. The STEP Part 21 file below shows the connection between the data of ISO 14649 and that of the developed data model.

Future work

The main scope of this work is to develop a data model for optimisation based on STEP-NC. Further development of process monitoring and control and a knowledge-based module is envisaged as future work. This may include,

1. Creating a protocol to interpret suitable set point signals representing vendor-specific information to incorporate in the current framework. The protocol is a set of rules to synchronize set point signals that are used by computers dealing with the signals representing vendor-specific information to regulate machine tool controls. It can be mathematically expressed as the roles governing the synchronized servo and encoder drive signals. The protocol may be implemented by both hardware and software switching configurations for different vendor-specific drivers.
2. Developing an EXPRESS schema for preserving signal information at the process control and monitoring level. The aim is to provide a generic data structure to give options for defining vendor-adaptive control algorithms and their drive signal information such as positions, velocity and motor current. A drive signal monitoring and control data model for actual process data containing references to STEP-NC data elements has been introduced by Wosnik et al. (2006). It might be considered and/or further developed to fit in the current framework. In this schema, entity *motor_current_observer* which is the subtype of entity *machined_workingstep_motor_current* is used for feeding back process forces which may require several measures including motor rotational speed and position. The concept of the feedback process force is to control the dynamic behaviour of the forces by means of subtraction of the sensed signal force from the previous machining situation with similar machining objects to create the error signal force. The error can be reduced by adjusting the speed. Thus, the process force calculation models may be updated and machining parameters be optimized.

Table 2 An example of cutting parameters for generating the native STEP-NC data

Parameters	Value
Vertical end-milling operation	
Main drive motor power	0.29 kW
Depth of cut	3 mm
Maximum allowable feed per tooth	0.5 mm/r
Cutting speed of HSS	35 m/ min
Specific cutting resistance	1,000 N/ mm^2
Workpiece length	300 mm
Mechanical efficiency	90%

3. Assigning agents to record data of the changed cutting parameters during machining operation. The cutting parameters to be recorded may include for example depth of cut for each steps, feed-rate, spindle speed, machining time and power consumption.

The developed data model can be considered to work alongside the *adaptive_control* entity for milling in ISO 14649 Part 11. The *adaptive_control* entity is a generic supertype for the vendor-specific adaptive control strategy. The current definition of adaptive control is an entity with no associated attributes. In 2009, NIST submitted comments on ISO 14649 adaptive control and redefined *milling_technology* entities as follow;

```
ENTITY milling_technology
  SUBTYPE OF (technology);
  its_speed:   speed_spec;
  its_feed:    feed_spec;
  synchronize_spindle_with_feed:BOOLEAN;
  inhibit_feedrate_override:  BOOLEAN;
  inhibit_spindle_override:  BOOLEAN;
END_ENTITY;
ENTITY speed_spec
  ABSTRACT SUPERTYPE OF (ONEOF
  (cutspeed, spindle_speed));
  adaptive_allowed:  BOOLEAN;
END_ENTITY;
ENTITY feed_spec
  ABSTRACT SUPERTYPE OF (ONEOF
  (feedrate_tcp, feedrate_per_tooth));
  adaptive_allowed:  BOOLEAN;
END_ENTITY;
```

The comment is to define *feed_spec* and *speed_spec* with a Boolean attribute named *adaptive_allowed*. If *adaptive_allowed* is true, machines with adaptive control may vary the feed and speed while machines without adaptive control must use the programmed value of the feed and speed. If *adaptive_allowed* is false all machines must use the programmed value of the feed and speed. Thus, the proposed optimization can be fitted in this attribute.

Conclusion

The drive for increased productivity, reduced production time and cost, reduced defective parts and relaxed machine design constraints, pushes for real-time control and optimisation for machining operations. Use of the STEP-NC data model brings design data such as geometry, tolerances and materials into process control and monitoring of machining operations, allowing a robust control mechanism. The newly developed EXPRESS schema for optimisation purposes augments the existing STEP-NC data models. This is necessary for an integrated environment in which high-level machine condition monitoring can be exercised for optimising machining processes. The EXPRESS data model aims to provide the necessary data for machining optimisation. Optimisation is carried out for two different scenarios: (a) maximizing feed-rate and depth of cut for time-critical machining operations (e.g. roughing operations) and (b) maximizing machining quality for QC machining operations (e.g. finishing operations).

The developed simulator verified the optimisation algorithm, the real-time process control and monitoring algorithm. It also validated the knowledge base. The significance of the proposed system lies in the fact that it can shorten the machining time and achieve the desired quality—all under the consideration of the machine capabilities and limitations. The next step of this research is physical implementation.

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