CRANFIELD UNIVERSITY

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Function Block Based Real-Time Tool Path Optimisation

School of Aerospace, Transport and Manufacturing

(School of Applied Sciences)

MSc by Research Thesis
Academic Year: 2013–2014

Supervisor: Dr Jörn Mehnen, Dr Ip-Shing Fan
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ABSTRACT

With the changing and increasingly more demanding global markets, also Computer Aided Process Planning (CAPP) gets challenged. Industry is expecting more adaptive, dynamic, intelligent CAPP systems to deal with the uncertainty and the increasing complexity of machining processes. Generally, high intelligence and automation are the tendency of industry. Conventional CAPP systems as well as off-line optimisation have been very well investigated over many years. However, well-optimised solutions developed for static environments still often need manual manipulation when dealing with uncertainty and dynamics.

As one of the emerging software technologies, Function Blocks have been introduced to deal with uncertainty in CAPP and manufacturing. The underlying hypothesis of this research is that Function Blocks delivered through the Cloud and deployed into a milling machine controller can provide real-time monitoring, optimisation and control.

In this study, a real-time Function Blocks based tool path optimisation for face milling system is proposed. The system can optimise feed rate and cutting speed to create stable cutting conditions in real-time based on measured dynamically fluctuating cutting forces.

ACKNOWLEDGEMENTS

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LIST OF ABBREVIATIONS

CAPP	Computer Aided Process Planning
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
FBs	Function Blocks
MRR	Material remove rate
FL	Fuzzy logic
EA	Evolutionary computing algorithm
GA	Genetic algorithm
HC	Hill climbing algorithm
CNC	Computer numerical control
COMAC	Commercial Aircraft of China
4DIAC	Framework for distributed industrial automation and control
FBDK	Function block development kit
FBench	Open source FB workbench

LIST OF SYMBOLS

b	Unformed chip width (mm)
C_r	Cutting resistance (N/mm^2)
e_t	Tooth pitch (mm)
f	Feed rate (m/min)
f_z	Feed per tooth (mm/tooth)
D	Tool diameter (mm)
d	Depth of cut (mm)
F_a	Active force (N)
F_c	Cutting force (N)
F_{cn}	Normal cutting force (N)
F_f	Feed force (N)
F_{fn}	Normal feed force (N)
F_{max}	Maximum cutting force for one cycle (N)
h_1	Unformed chip thickness (mm)
N	Spindle speed (rpm)
V	Cutting speed (m/min)
z	Number of cutting edges
$\emptyset_i$	Cutter rotation angle (°)
α	Angle between two cutting edges (°)
σ	Touching angle (°)

1 Introduction

1.1 Background

During generic machining processes, the following five essential steps are followed, as proposed by Ranky (1983); manufacturing sequencing, tool and machining setup, tool path and NC data creation, simulation and machining. Each step will have a strong influence on production time and cost, thus Computer Aided Process Planning (CAPP) is used to assist.

However, as the global market changes, conventional CAPP is challenged. More adaptive, dynamic, intelligent CAPP systems are required to deal with the increasing complexity of machining processes (Xu et al., 2011). Currently, CNC machines run using G-code, which is generated normally by CAx software such as Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM). Once the G-code is generated and executed by the CNC machine, the tool path setup, as well as other parameters, cannot be adjusted. If something unexpected happens during a machining process, such as cutting force overload and heavy vibration, human expertise is needed to adjust the feed rate or the spindle speed manually. Any major changes to part of the design, machine tool or fixtures require the engineers to re-generate the G-code through the long CAD-CAM chain.

Reducing time consuming and repetitive manual work and increasing high rates of automation is the aim of the modern industry. Leaders of the CNC controller manufacturers, such as Heidenhain, Haas and Mazak, have updated the real-time monitoring and feed rate control systems in their products. However, most of the systems can only realise basic real-time controls, and cannot carry out real-time optimisation. Currently, most of the systems were designed based on expert knowledge models, for example, the system will come with some pre-set grades, the monitored value will be compared to a reference value and the system will then make a decision based on which grade the current value has.

Often these system are not adaptive enough to the demands of the industry, therefore a more efficient and intelligent system is required, which can realise real-time monitoring and optimisation.

1.2 Research motivation

The research is under the EU project: Collaborative and Adaptive Process Planning for Sustainable Manufacturing Environments (CAPP-4-SMEs). The aims of the CAPP-4-SMEs project are:

- Innovative and adaptive process planning to support SMEs (Small- and Medium-sized Enterprises) in order to achieve cost-effectiveness, sustainability, smartness.
- knowledge-based simulation system to achieve first-time-right
- Event-driven function block for on-line real-time control.
- Cloud platform to achieve portable and remote control and resource sharing.

Using FBs to realise on-line and real-time control and optimisation of the feed rate and cutting speed is the purpose of this study. The aim of this research is tied to the aims of the CAPP-4-SMEs project, in particular to equip CNC machines with more intelligence and support automation to benefit the shop floor.

1.3 Project scope

The scope of this research covers

- the identification of classic machining parameters that can be optimised to influence tool paths,
- the parameters that influence the behaviour of FBs to achieve optimised tool paths (i.e. the results will comply to the ISO standard of FBs),

- the way current CNC controllers behave in real-time control (i.e. the study does not concern the variation of any existing CNC controller itself),
- the selection and implementation of suitable existing objective functions and existing algorithms to realise real-time feed rate and cutting speed optimisation (i.e. the study may only concern minor variations of existing best-practice optimisation algorithms).

1.4 Work definition

Usually when talking about real-time, it refers to short, quick action within a certain zone. The ideal real-time could be zero, which is clearly not possible or realistic. Therefore, in industry when talking about real-time, it normally refers to a certain period of time, such as within 50ms.

In this study, real-time refers to the expected running time of a programme is within 50ms. The reason 50ms is chosen as the boundary is that normally the CNC controller needs around 10ms to react with the command (for detailed reaction times of different CNC controllers, see APPENDIX C). The CNC machine reacting to the command, such as increase or decrease of feed rate, will also need time because the machine needs to accelerate or decelerate. The acceleration or deceleration time will depend on the workpiece and the size of the CNC machine; normally 10-20ms is needed. Furthermore, some extra time has to be reserved for future work such as adding other objective functions.

1.5 The collaboration company

The Commercial Aircraft Corporation of China (COMAC) is the civil aircraft manufacturer owned by the Chinese government. COMAC have three different workshops which manufacture metal parts. The workshops have more than 10 years of the CAPP experience and they are interested in new development of the field.

PowerKut Limited is a family-run business which provides products for rail, mining, aerospace and many other industries. PowerKut is one of the SME partners of the EU project CAPP-4-SEMs.

1.6 Aim and objectives

The aim of this research is to create a light-weight optimisation programming framework work for creating function blocks that can influence the behaviour of CNC machining controllers to realise real-time tool path optimisation.

The objectives are:

- Capture the factors in milling processes and analyse the factors that are used by researchers for optimisation.
- Knowledge acquisition on the methods of optimisation and objective functions such as time function, cost function and cutting force function.
- Capture the properties and advantages of Function Blocks. Learn what CNC controllers are doing in adaptive control.
- Develop time-efficient functions for calculating total cutting force values based on measured dynamic process values.
- Build a FB based framework which can realise real-time adjustment of feed rate or cutting speed according to real-time cutting force signals.
- Validate the proposed optimisation system though a case study to prove that the real-time optimisation system can stabilise cutting forces.

1.7 Thesis structure

The thesis is composed of seven chapters (see Figure 1-1). Chapter 1 includes the background, research motivation and scope, aim and objectives. Chapter 2 introduces the knowledge collected from literature about topics such as milling, Function Blocks, optimisation methods and CNC controllers. Chapter 3 provides the method of the research, the way how the study was carried out. Chapter 4 gives the detail of the data collection, provides the results and analysis of the questionnaire. Chapter 5 provides the process of the system build, the initial thoughts and the final model. Chapter 6 brings the validation though testing and the case study. Chapter 7 gives the conclusion and discussion for future research.

1.8 Summary

This chapter introduces the background, research motivation and scope, problem statement, aim and objectives, and the structure of the thesis. The purpose of the chapter is to tell the background of the research, why the study is worth.

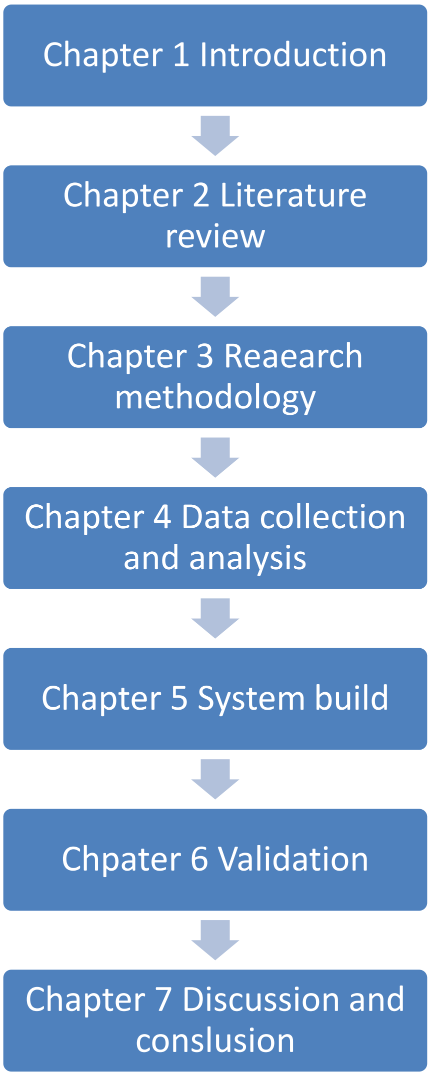

Figure 1-1 Structure of the thesis

2 Literature review

2.1 Literature review structure

The subject of the optimisation of milling processes is wide and a lot of research has been previously carried out in this area. The literature review scope covered the most recent studies. This section reviews milling machines and operations, milling optimisation, optimisation methods, optimisation objective functions, CNC controllers and Function Blocks.

The structure of the literature review is shown in Figure 2-1.

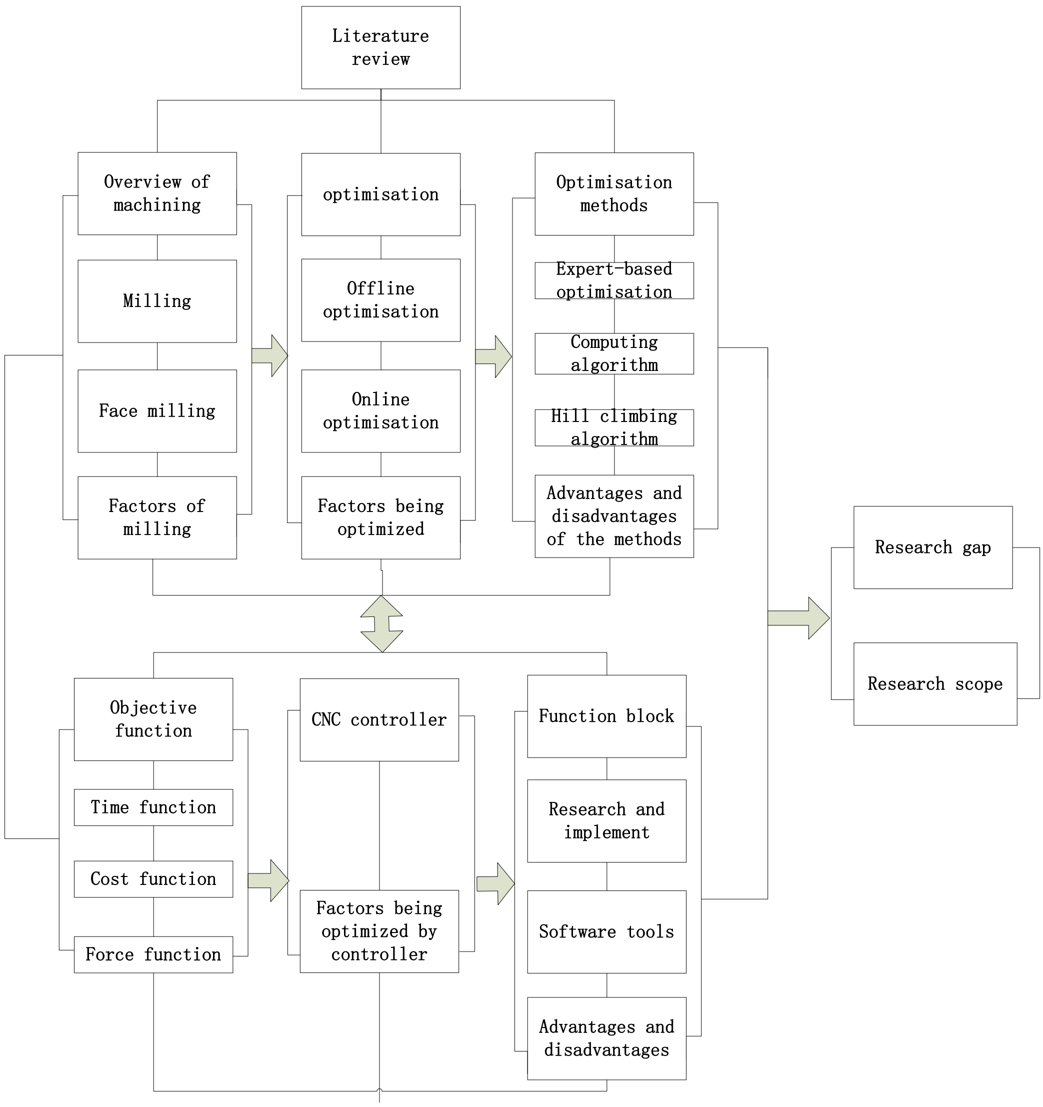

Figure 2-1 The structure of the literature review

2.2 Overview of machining

Machining, as a family member of "material removal processes", is conventionally described as "using sharp cutting tools to remove material in order to get the desired geometry" (Groover, 2010). Figure 2-2 shows the flow of "material removal processes". There are three basic processes of machining; turning, drilling, and milling.

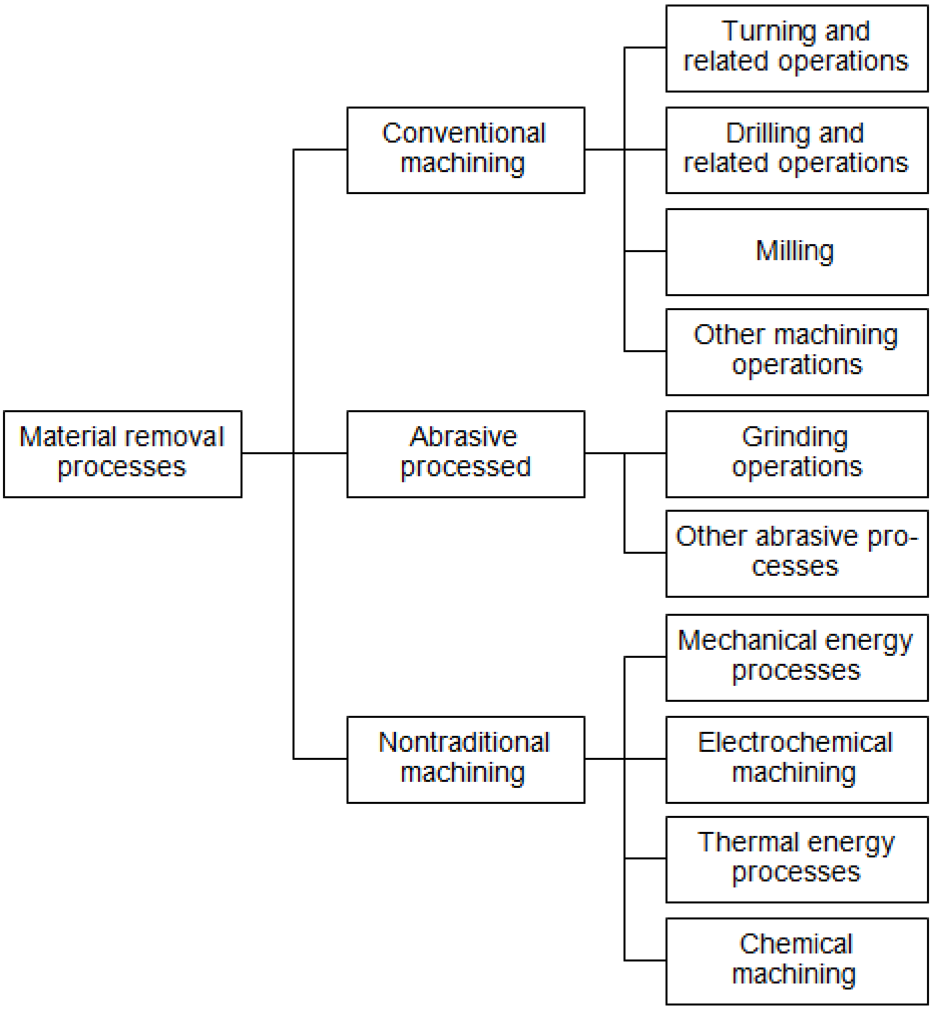

Figure 2-2 The classification of "material removal processes"

Machining as the foundation of modern manufacturing processes contributes to the revolution and increase of the manufacturing-based economy (Groover, 2010). Table 2-1 shows the advantages and disadvantages of machining.

Table 2-1 The advantage and disadvantage of machining (Groover, 2010).

Advantage	
Variety of work materials	Almost all solid metals, Plastics, Composites
Variety of part shapes and geometric features	Almost unlimited complexity and variety of shapes
Dimensional accuracy	Very high accuracy
Good surface finishes	Very smooth surface finishes
Disadvantage	
Wasteful of material	Material cut from the part are wasted
Time consuming	Takes more time than casting or forging

2.2.1 Milling

Milling is a machining process which normally uses multi-toothed tools to generate a free-shape surface with a circular cutting rotation (Klocke, 2011).

There are two forms of milling, namely face milling and peripheral milling (end milling is a very common type of peripheral milling). Face milling refers to the workpiece surface being manufactured by the minor cutting edge of the tool's front face. Peripheral milling means that the surface of the part is manufactured by cutting the edges peripherally (Klocke, 2011). Figure 2-3 shows face milling and peripheral milling.

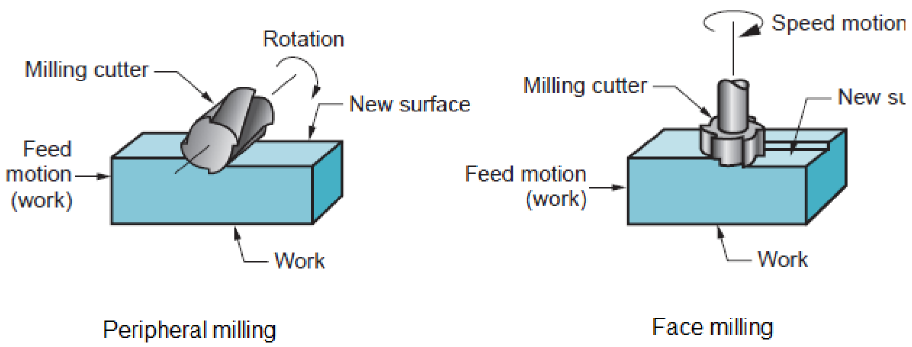

Figure 2-3 Face milling and Peripheral milling (Groover, 2010)

2.2.2 Face milling

Face milling is widely used in industry as a very important method of machining. Face milling can provide high efficiency and capability in generating complex structures, as well as being low in cost (Tlusty, 2000). Figure 2-4 shows face milling in further detail.

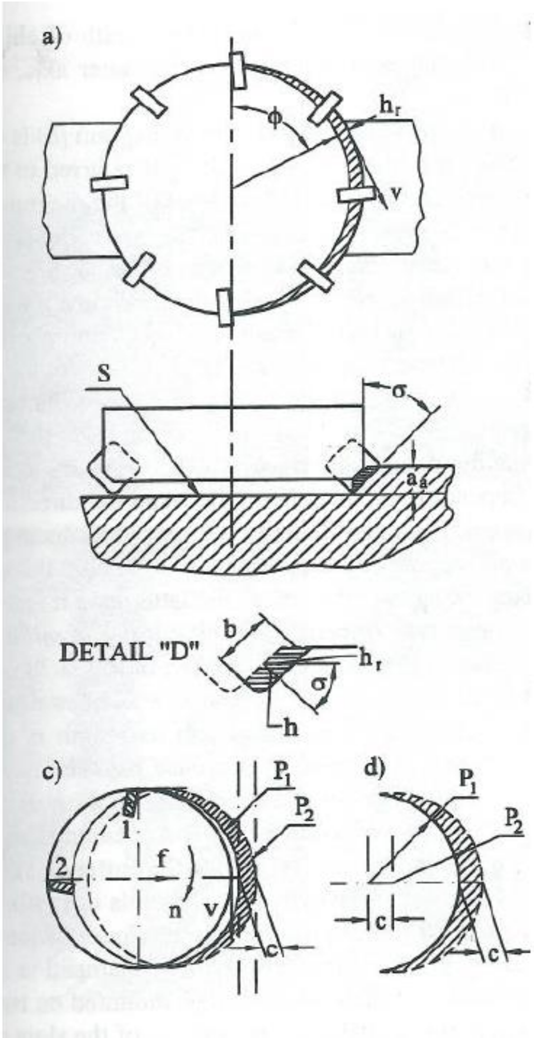

Figure 2-4 Face milling (Tlusty, 2000)

2.2.3 Milling factors

The milling process is complex because there are several different factors involved in the process and even a slight change of these factors can impact on the quality of the milling result. The basic factors of a milling process are; feed rate, spindle speed, cutting speed, depth of cut, width of cut, chip thickness, lubrication and MRR (metal removal rate).

Feed rate f (mm/sec) in milling operations is performed either by the cutter or by the workpiece, as shown in Figure 2-3**Spindle speed** n (rev/sec) is the rotation of the cutter as shown in Figure 2-3. **Cutting speed** v (m/sec) is the peripheral speed of the cutter as shown in Figure 2-4. **Depth of cut** a_a(mm) is the depth of the edge cut into the material as Figure 2-4 shows. **Width of cut** a_r (mm) is the width of the layer cut from the workpiece. **Chip thickness** h (mm) is the thickness of the material removed from the workpiece by the tooth of the tool. **Lubrication** is a solid or liquid added to the surface to help reduce the wear and carry the load. **MRR** (cm^3/min), as the title suggests, is the speed of the material removed from the workpiece.

2.3 Optimisation

Metal cutting technology has become a very important method in global manufacturing. Manufacturing enterprises have to response quickly to global competition by using optimisation methods to achieve high efficiency, high quality and low cost (Mukherjee et al., 2006).

The research into optimisation is focused on the geometry of the tools, the material of the workpiece, and the parameter settings (Mukherjee et al,. 2006). Among these three factors, parameter optimisation is probably the most popular in recent years.

Off-line optimisation and on-line (real-time or adaptive) optimisation are the most basic forms of optimisation used within industry. Researchers have been focused on these subjects for years, and many optimisation methods have been developed. Due to the complexity of machining processes, all existing methods, to some extent, have limitations which mean that they can not satisfy all the demands of industry.

2.3.1 Off-line optimisation

Off-line optimisation is one of the most important steps in real-life manufacturing processes. Normally, optimisation is carried out using professional software. First, the parameters of machining are set based on handbooks. These settings need to be optimised and simulated using software to gain new and better settings of the parameters. The optimisation step will provide a stable, efficient and safe machining process, at low cost.

There are many advantages of off-line optimisation. Because off-line optimisation is not limited by time, the system can be as complex as it needs to be, and multi-factors and multi-objectives can be achieved. Table 2-2 shows a list of 38 off-line optimisation papers, dating from 1994 to 2014. As Figure 2-5 shows, nearly 60% of these papers were written between 2010 and 2014, which gives a reflection on where research has been focused in recent years. Two important considerations are shown in Table 2-2; which are the most common factors to be optimised and what are the most objectives focused on. A more detailed analysis is provided in Chapter 2.3.3. Optimisation and milling were used as keywords for searching through websites: http://www.sciencedirect.com, http://scholar.google.co.uk. Table 2-2 shown below is part of the whole table, the complete table is given in Appendix A.

Table 2-2 List of off-line optimisation research

Writer	Optimised factors	Objectives
Yildiz, 2013	Optimise feed	Maximum production rate
Zain et al., 2010	Optimise feed cutting speed radial rake angle	Minimum surface roughness
Chu et al., 1997	Optimise feed	Reduce production time
Peres et al., 1999	Optimise feed MRR	Stabilise cutting force
Baek et al., 2001	Optimise feed	Minimum surface roughness

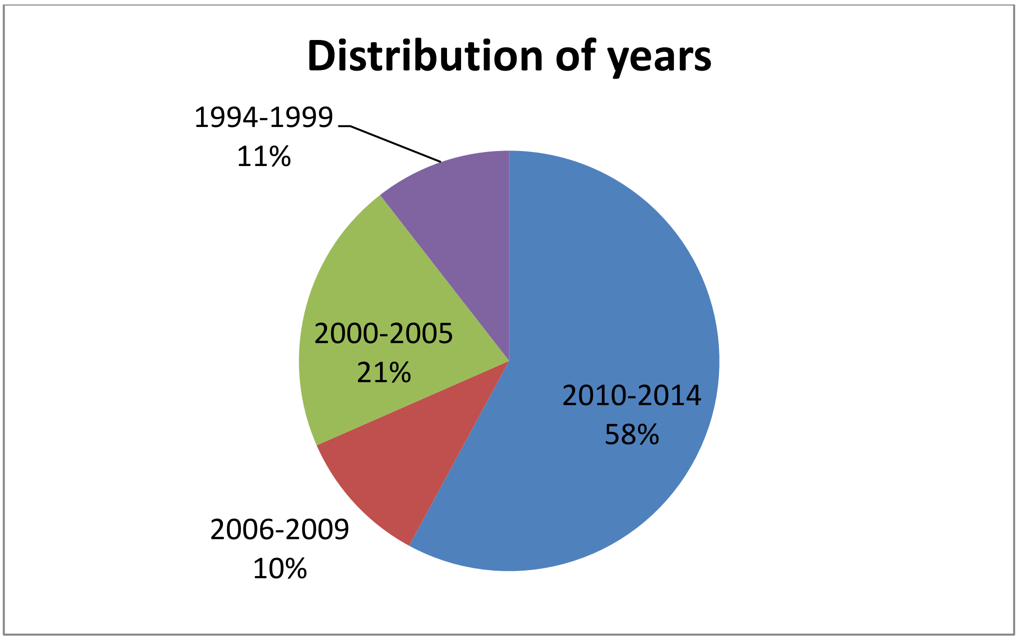

Figure 2-5 The distribution of years (off-line optimisation papers)

2.3.2 On-line optimisation

On-line optimisation can also be regarded as real-time or adaptive optimisation. The advantages of on-line optimisation compared to off-line are the cost and efficiency (Pistikopoulos et al., 2002). Normally, the input value of on-line optimisation is measured using a CNC machine. On the other hand, the input value of an off-line system is predicted by calculation. This makes the output value of an on-line system more accurate.

However, on-line optimisation also has many limitations; on-line calculation ability being the primary problem (Pistikopoulos et al,. 2002). The calculation ability of the computer will determine the speed and the complexity of the system. Thus the key to on-line optimisation is a high speed computer and light-weight programme. Table 2-2 shows a list of 12 on-line optimisation theses dating from 1994 to 2014. As Figure 2-6 shows, nearly 85% of these theses were written after 2005, which reflects where the research has been focused on in recent years. Two important considerations are shown in Table 2-3; what are the most common factors being optimised and what are the most common objectives focused on. A more detailed analysis is provided in Chapter 2.3.3. On-line, real-time, adaptive, optimisation was used as keywords for searching through websites: http://www.sciencedirect.com, http://scholar.google.co.uk. Table 2-3 shows below is part of the whole table, see the whole table in Appendix B.

Table 2-3 List of on-line optimisation research

Writer	Optimised factors	Objectives
Cus et al., 2006	Optimise feed cutting speed depth of cut	Stabilise cutting force Reduce production time
Milfelner et al., 2005	Optimise feed cutting speed depth of cut	Increase machining efficiency
Bosettia et al., 2013	Optimise feed spindle speed	Stabilise machining process Increase machining efficiency
Chiang et al., 1995	Optimise feed	Increase machining efficiency
Zuperl et al., 2005	Optimise feed	Reduce tool wear Reduce production time

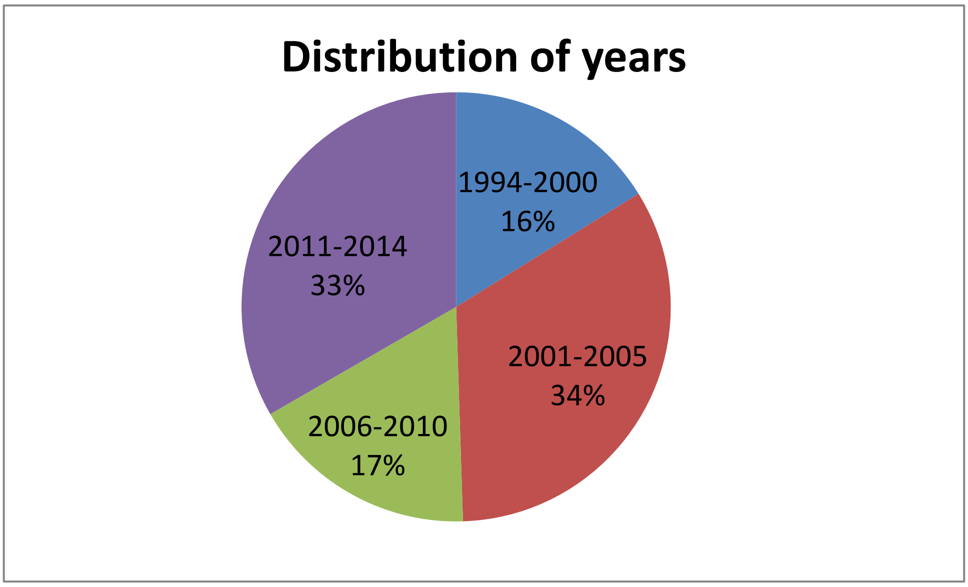

Figure 2-6 The distribution of years (on-line optimisation papers)

2.3.3 Factors being optimised

It is easy to observe the most common factors and objectives from the literature review, as Table 2-2 and Table 2-3 shows. Following analysis of these two Tables, Figure 2-7 and Figure 2-8 could be easily produced. Figure 2-7 shows the popularity of the factors within off-line optimisation; it is obvious that feed is the most common factor and nearly 70% of researchers decide to target it for optimisation. Cutting speed and depth of cut are the second most common factors; spindle speed and MRR the third; followed by the tool path as the fourth. The same situation happens with on-line optimisation, as Figure 2-8 shows. Feed, no doubt is the number one most common factor, with cutting speed and depth of cut being second, and spindle speed and tool path third.

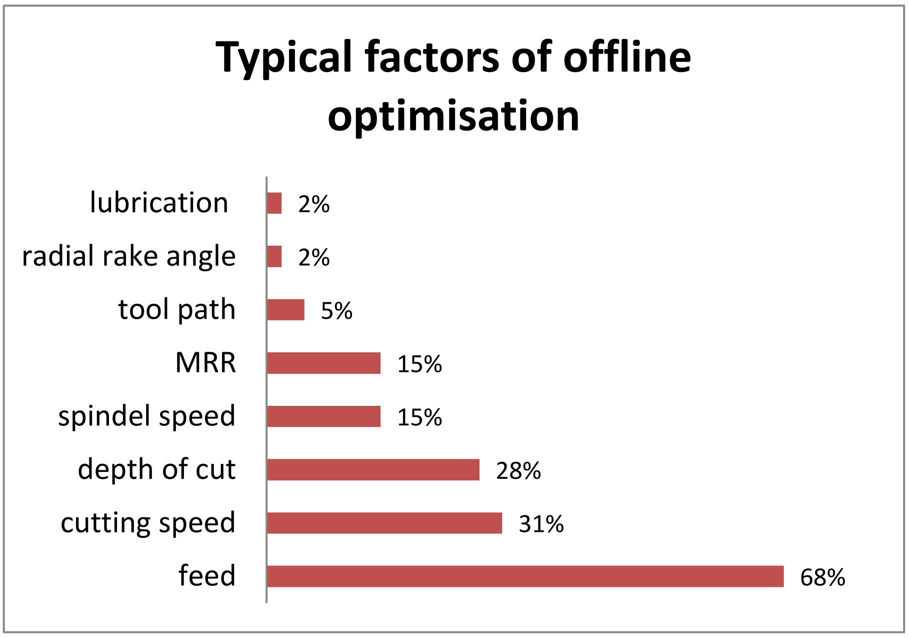

Figure 2-7 Typical factors of offline optimisation

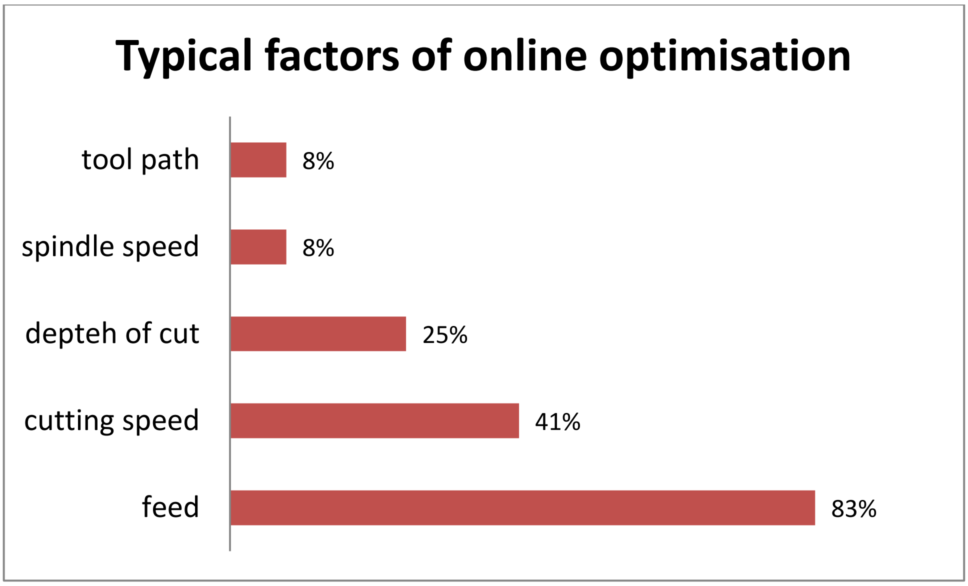

Figure 2-8 Typical factors of online optimisation

It is clear that feed, cutting speed and depth of cut are the most common factors in both off-line and on-line optimisation in recent years. Figure 2-9 and Figure 2-10 show the results of an analysis of the objectives of Table 2-2 and Table 2-3. The distribution of objectives is not so dramatic compared with the optimised factors. The most common objectives of the studies focus on time and cost (approximately 30%). For off-line optimisation, surface roughness (18%) and cutting force (10%) follow on as the second and third most common, and for on-line optimisation, cutting force (25%) and tool wear (16%) follow on as the second and third most common. Vibration, tool wear and machine error are the other more common objectives of off-line optimisation, while power consumption, the deformation of the part and spindle current are less common.

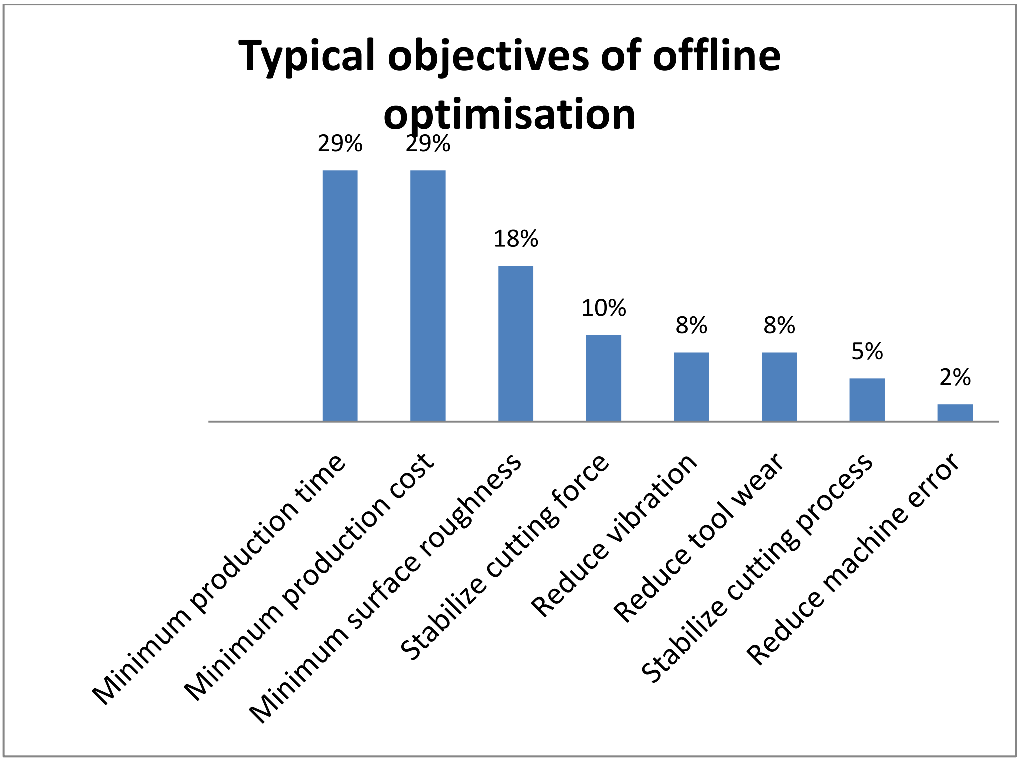

Figure 2-9 Typical objectives of offline optimisation

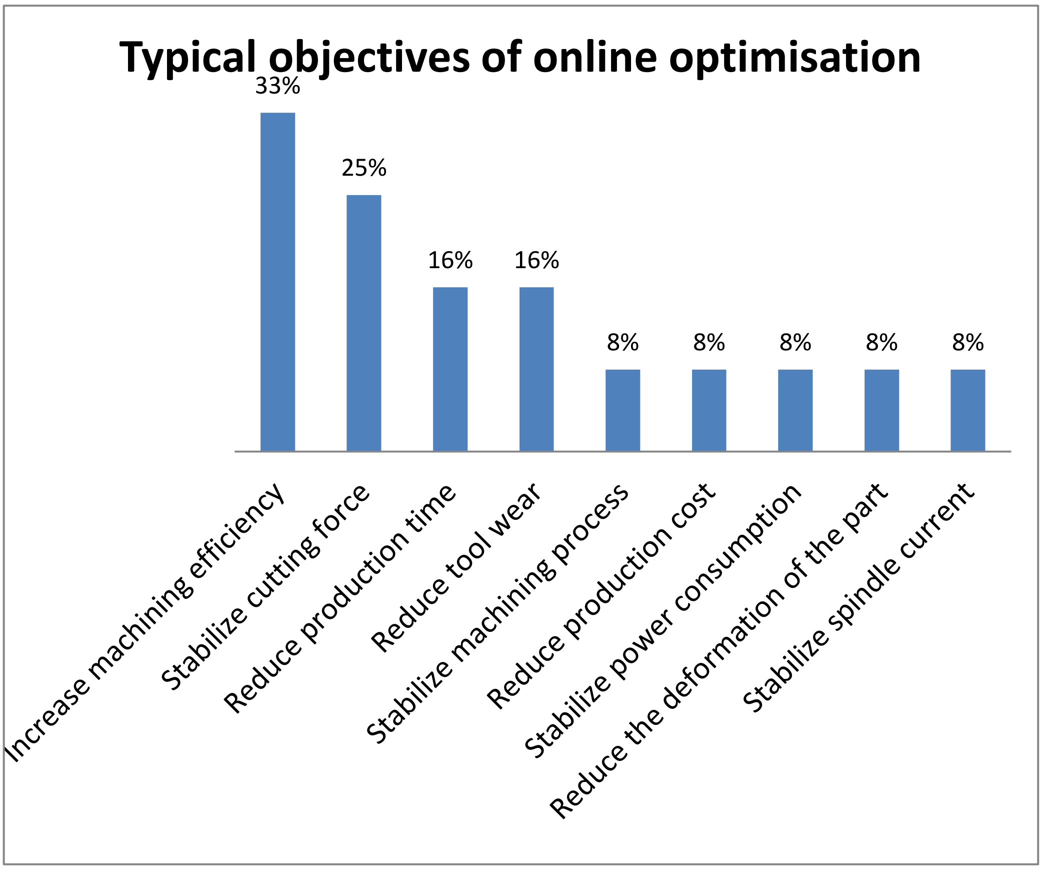

Figure 2-10 Typical objectives of online optimisation

2.4 Optimisation methods

Different kinds of optimisation methods are developed to satisfy the increasing demands of optimisation within industry. Essentially, optimisation methods can be classified into three main groups: expert-based optimisation, Design of Experiment (DoE) based optimisation, and computing algorithms (Roy et al., 2008). Within the scope of this paper, mainly expert-based optimisation, but also partly computing algorithms, are discussed in further detail.

2.4.1 Expert-based optimisation

Expert-based optimisation usually applies expert judgement as the core logic for optimisation. There are a few advantages of this method, such as no additional techniques are needed to be utilised by the designer; it is usually faster to find the optimum to make it possible to gain continuous improvement (Roy et al., 2008). However, the limitation of the method is also obvious; it is limited to the knowledge of the designers and the experts, meaning that the system has no ability to deal with unknown situations. In addition, to some extent, the system may be subjective depending on the knowledge of the experts. In this paper, two typical expert-based optimisation methods are discussed; Expert systems and Fuzzy logic.

2.4.1.1 Expert systems

Expert systems can be a very useful method for assisting any machining process. Basic data and criteria must be generated through experiments or mathematic models, or a combination of the two.

Optimised factors are measured and then, at the input of the system, the input data will be compared to the internal criteria. After this comparison, the system will make a decision and generate the optimised value which can satisfy the requirements of the process (Martín et al., 2010). Figure 2-11 shows the typical programme and logic of expert system.

```
  | (defrule cut-strength-7[3]
1 |   (state cut-strength 4 4)
2 |   (assumed-risk 3)
3 |   (control spindle ?vs&:(< ?vs 105))
4 |   (control coolant ?vc)
  |   =>
5 |   (assert (action cut-strength 4 4 spindle (+ ?vs 5)))
6 |   (if (< ?vc 10)
  |       then (assert (action cut-strength 4 4 coolant (+ ?vc 5)))))
```

Figure 2-11 Example of expert system (Martín et al., 2010)

2.4.1.2 Fuzzy logic

Fuzzy logic (FL) was first proposed in 1965 by Zadeh, who is regarded as “the father of fuzzy logic”. Following his work, a large amount of research has been carried out in this field. In industry, human experts are making judgements based on common sense and their experience, which is usually not precise. This process can be expressed by fuzzy variables and rules, if the design of the fuzzy system is well organised, and can perform as efficiently as human experts (Jamshidi et al., 1993).

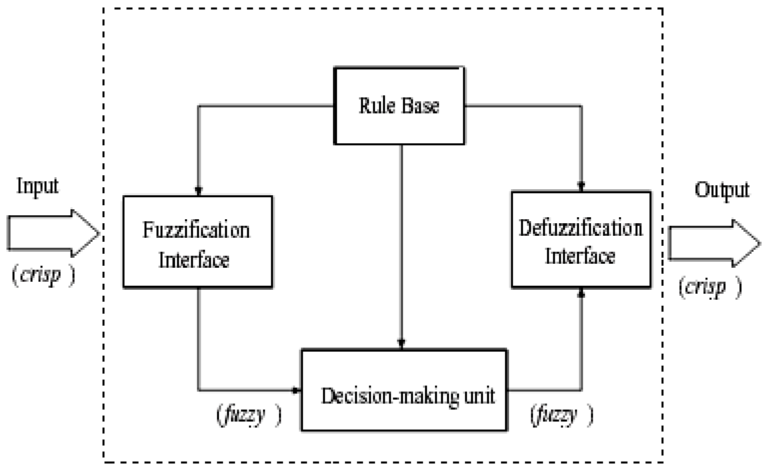

Figure 2-12 Basic fuzzy logic system (Abreu et al., 2003)

Figure 2-12 shows a basic fuzzy logic system. A linguistic or crisp value is entered into the system and then transferred to linguistic or fuzzy membership functions through fuzzification. The value then goes through the “IF-THEN” rules to make the decision and generate the output. This output will transfer to crisp values through a process called de-fuzzification.

2.4.2 Evolutionary Computing algorithm

Evolutionary computing algorithms (EA) follow a heuristic search approach, in which the search is stochastic and based on rules similar to the evolution of nature (Brankel, 2002).

Starting with a population of candidates, based on the fitness of the environment, the best candidates are selected to form the next generation. By applying recombination and mutation, parents and offspring are generated. The offspring will compete with their parents for a ticket for the next generation. This process can be repeated until a solution is found, as Figure 2-13 shows (Eiben et al., 2002).

```
Initialize population with random
  individuals (candidate solutions)
Evaluate (compute fitness of) all
  individuals
WHILE not stop DO
  Select genitors from parent population
  Create offspring using
    variation operators on genitors
  Evaluate newborn offspring
  Replace some parents by some offspring
```

Figure 2-13 General scheme of EA (Eiben et al., 2002)

Genetic algorithm (GA) is the most well-known evolutionary-based method (Yildiz, 2013), first proposed by John Holland in early 1970’s. In the last few decades, GA has become the most popular optimisation algorithm (Roy et al., 2008). Evolutionary-based algorithms are usually used for parameter optimisation, especially for multi-objective optimisation (Deb, 2001).

2.4.3 Hill climbing algorithm

Hill climbing algorithm (HC) is an optimisation approach which begins with a given original solution (a value). The value will keep changing, and the objective function will evaluate the new value until it reaches the local or global optimum (Taborda et al., 2012).

Simplicity is the main advantage of hill climbing algorithms (Schwefel, 1993). The algorithm is more suited to finding local optima (Forrest et al., 1993), however, the hill climbing algorithm method is criticised for its inability to find the global optimum, especially when applying the method on multi-objective and non-linear optimisations.

2.4.4 The advantages and disadvantages of above methods

A survey of five UK companies within aerospace and automotive industries shows that expert-based optimisation is the method applied most commonly within industry, whereas the evolutionary computing algorithm is not as common(Roy et al., 2008). Table 2-4 shows the advantages and disadvantages of the three main methods. Expert-based optimisation is the favoured and most widely used approach because it is efficient in modelling human experts and adaptive control. The drawbacks of the method are that the knowledge data base depends on the particular experts involved, which is subjective and may be incapable of dealing with uncertainty. Evolutionary computing algorithms are powerful and suitable for multi-objective optimisation, as almost any problems which could occur within to formulae can be optimised through this method. The disadvantage of this method is that it is time consuming compared to other popular methods such as expert-based optimisation. The advantages of hill climbing algorithms are the simplicity and efficient performance when dealing with single objective optimisation. However the drawback is sometimes fails to find the global optimum.

Table 2-4 The advantages and disadvantages of the three methods

	Advantage	Disadvantage
Expert–based optimisation (expert system ,fuzzy logic)	●Model human expert operator ●Suitable for real-time control	●Subjective ●Incapable of dealing with uncertainty
Evolutionary computing algorithm （EA, GA)	●Broad applicability ●Suitable for multi-objective optimisation	●Time-consuming compared with others
Hill climbing algorithm	●Simplicity	●Accuracy depending on the step size ●Sometimes failed to reach the global optimum

2.5 Objective function

An objective function is typically used for the optimisation of maximum or minimum values (Pintarič et al., 2006). The objective function is the bridge that connects the factors to be optimised with the objectives. The factors as inputs of the objective function and the outputs are usually the maximum or minimum value of the objectives. Objective function is very important in optimisation process, as the calculation and evaluation will depend on it. In this paper, as shown in Chapter 2.3.3, the current most popular objectives are minimising production time and cost, and stabilising of cutting force. The relevant objective functions are discussed below.

2.5.1 Time function

Time function, as the title suggests, aims to minimise the production time of every production cycle. Machining parameters such as feed and cutting speed are inputs of the function, which are then calculated by the time function and evaluated together with constrains such as tool life and power consumption.

The outputs will usually be the combination of machining parameters which will meet the minimum production time. The following time functions are taken from Sönmez et al., 1999.

$$T_{pr} = T_p + T_L + T_a + T_m + T_c \qquad (2)$$

T_{pr} is the production time per part for a machining process. T_p (min) is the machine preparation time, and can be expressed as Eq. (3). T_L (min) is the loading and unloading time. T_a (min) is the adjusting and return time. T_m (min) is the machining time. T_c (min) is the tool change time, and can be expressed as Eq. (4).

$$T_p = \frac{T_s}{N_b} \qquad (3)$$

T_s (min) is the setup time for a group and N_b is the number of parts in the group.

$$T_c = \frac{T_m \cdot T_d}{T} \qquad (4)$$

T_d (min) is the time taken to replace tools and T (min) is tool life. T_m can be expressed as:

$$T_m = \frac{L}{f} \qquad (5)$$

L (mm) is the length of a cut and f (mm/min) is the feed rate.

$$f = f_z \cdot z \cdot N \qquad (6)$$

f_z (mm/tooth) is the feed per tooth, z is the number of teeth on the cutter, and N (rep) is the spindle speed, which can be expressed as:

$$N = \frac{1000 \cdot V}{\pi D}$$

V (m/min) is the cutting speed, and D (mm) is the diameter of the cutter.

The Eq. (2) thus can be expressed as:

$$T_{pr} = \frac{T_s}{N_b} + T_L + T_a + T_m + T_d \left(\frac{T_m}{T}\right) \qquad (7)$$

Feed rate, cutting speed and feed per tooth are inputs of the time function. These inputs will be evaluated together with constraint functions such as power function, cutting force function and surface roughness function, and the outputs will be the new value of input parameters.

2.5.2 Cost function

Cost function is much like time function, the differencebeing that the purpose of the function is to minimise the cost of each machining process. The following cost function for face milling was introduced by Shunmugam et al., 2000;

The general cost of a single pass of face milling can be described as:

$$U= k_o t_m + (k_t z)\frac{t_m}{T_R} + k_1 t_m \left(\frac{t_e z}{T_R}\right) + k_0(Lh_1 + h_2) \quad (8)$$

The first section of Eq. (8) is the machine cost, the second is the cost of tools, the third is the cost of tool replacements, and the forth is the idle motion cost of the tool. t_m is machining time as Eq. (9) shows;

$$t_m = \frac{L_t}{zfN} \quad (9)$$

L_t is the length of the cutter run, z is the number of teeth on the cutter, f is the feed rate and N is the spindle speed.

Similar to the time function, the minimum result of cost function needs to be evaluated with constraint functions such as power function, tool life function and cutting force function.

2.5.3 Cutting force function

The resultant cutting forces in the milling process can be described as either an active force F_a or a passive force F_p. Normally, the direction of F_a is dependent on the feed direction angle φ. The components of F_a can be expressed in two forms; cutting force F_c and cutting normal forceF_{cn}, or feed force F_f and feed normal force F_{fn}, as Figure 2-14 shows (Klocke, 2010).

Adolfsson et al, (1995) proposed the formula to calculate the feed normal force F_{fn}, as Eq.14 shows and the method to measure the F_{fn} in real-time face milling. They also proposed the formula to calculate the chip thickness, as Eq. 11 shows.

$$F_{fn} = C_r h_1 b_1 \quad (10)$$

C_r is the cutting resistance of the workpiece, which is different according to the material used. Meanwhile, C_r rises when decreasing the chip thickness; in this paper the change of C_r is very slight according to the chip thickness, and C_r is regarded as constant. h_1 is the unformed chip thickness, which is very important in the calculation of the cutting force. The unformed chip thickness is related to the feed rate, cutting speed, the number of cutting edges and the cutter rotation angle. The formula of unformed chip thickness is the key to building the relationship between feed rate and the cutting force. b_1 is the width of the unformed chip.

$$h_{li} = \frac{f \cdot e_t}{v} \sin \emptyset_i \quad (11)$$

Where f is feed rate and $\emptyset_i$ is cutter rotation angle. V is the cutting speed and e_t is the tooth pitch, which can be expressed as:

$$e_t = \frac{\pi D}{z} \quad (12)$$

π is the mathematical constant representing the ratio of a circle’s circumference to its diameter. D is the diameter of the cutting tool, and z is the number of cutting edges. The formula relevant to feed rate and cutting speed can be expressed as:

$$f = f_z \cdot z \cdot N \quad (13)$$

f_z is feed per tooth, and N is spindle speed which can be expressed as:

$$N = \frac{1000v}{\pi D} \quad (14)$$

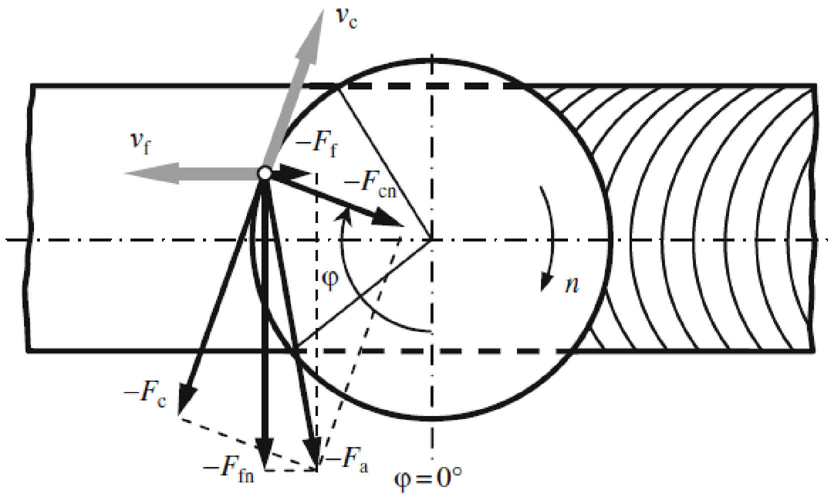

Figure 2-14 Cutting force model (Klocke, 2010)

Feed rate is related to cutting force, and the change of feed rate will change the unformed chip thickness and furthermore change the cutting force. Recently, the monitored cutting force could cover three scenarios; initial errors of cutting edge position, unexpected tool movements and cutting edge degradation (Andersson et al., 2011). The properties of the cutting force make it an ideal factor for building a real-time control system.

2.6 CNC controller

The CNC controller has an important role in the CNC machine system, because it controls the motion of the tools and machining operation automatically and intelligently (Yamazaki et al., 1997). To some extent, the CNC controller is the "head" of the CNC machine; it controls all the action of the machine, and collects data during the operation. The collected data will be analysed and reused to improve the quality of the machining process.

Currently, the development of future CNC controllers is open and more intelligent (Xu et al., 2012). Dissimilar to traditional CNC controllers, open CNC controllers normally use Microsoft Windows as the software platform and use a PC as the hardware platform (Xu et al., 2012). World famous CNC controller manufactures such as Fanuc, HEIDENHAIN and SIEMENS have already introduced their new models which are based on the Windows operating system (OS) platform, as Figure 2-15 shows. Windows based operating system can support the running of FBs, but so far the main CNC controllers did not apply FBs on their products.

Currently, the internal memory of the CNC machine is small, as Figure 2-15 shows, 1MB is the standard size for Fanuc, Haas and SIMENS. Others like Mitsubishi only have around 200KB internal memory. Programmes had to transferred into the CNC machine block by block because the internal memory is small. That is also the reason why a light-weight programme framework is necessary for this study.

As the competition increases in the global market, CNC controllers are faced with new challenges. There is demand for the next generation of controllers to be more intelligent, more automatic, and more adaptive. Leaders in the manufacture of CNC controllers such as Haas, HEIDENHAIN and Mazak have delivered new models with adaptive controls and real-time monitoring systems. These controllers will monitor the load or the vibration in real-time, and automatically adjust the feed rate based on the signal, as Figure 2-15 shows.

However, there is still space for the improvement of adaptive CNC controllers. Currently, the CNC controller will compare the monitored signal with limitations, and adjust the feed rate accordingly. CNC controllers such as HEIDENHAIN, the minimum adjustment like feed rate overwrite is 1%. This process is real-time control, not real-time optimisation. See the whole table in Appendix C.

Company	Market share of 2012	Products	Adaptive control or not	System requirement	Function block	Memory
Fanuc	26%	Series 30i / 31i / 32i		windows	NO	1-8MB
		Series 35i		windows	NO	Up to 1MB
		Series 0i		×	NO	Up to 1MB
		Power Motion i		windows	NO	Up to 2MB
Haas	14%		Real-time monitoring:tool load,Adjust feed rate according to tool load	×	NO	1-750MB
		Series Mini Mill		×	NO	1-750MB
		Series VF		×	NO	1-750MB
		Series VS		×	NO	1-750MB
		Series VF-TR		×	NO	1-750MB
IEIDENHAI	9%	TNC 128	Real-time monitoring: spindle power Adjust feed rate according to spindle power	×	NO	1.8GB
		TNC 320		×	NO	300MB
		TNC 620		windows	NO	1.8GB
		TNC 640		windows	NO	hard disk>21GB
		ITNC 530		windows	NO	hard disk>21GB
		CNC PILOT 4290		windows	NO	hard disk>21GB
		CNC PILOT 640		windows	NO	1.8GB
SIEMENS	5%	802D sl		×	NO	256KB
		808D		windows	NO	1.25MB
		828D		×	NO	Up to 5MB
		840D sl		windows	NO	9-15MB
Mitsubishi	4%	M700V		windows	NO	2000KB
		M70V		×	NO	500KB
		Series C70		×	NO	Max 2000KB
		Series 60S		×	NO	230KB
		Series E60/E68		×	NO	230KB

Figure 2-15Table of main CNC controllers and products(all of the data above were collected from the specifications of controller companies)

2.7 CNC system

2.7.1 CNC architecture

Common CNC system is composed of mechanical feed drives, motors, amplifiers, position and velocity acceleration sensors, and real-time system for positioning (Yeung et al., 2006). Figure 2-16 shows the traditional structure of CNC system (Wang et al., 2014). In general, controllers, motor and drive system, and machine & tool are three basic parts of CNC system. The CNC controllers control the position of different axis and their accelerations and decelerations. The controller receives and processes the feedback signal for further positioning. Figure 2-17 shows the structure of drive system (Yeung et al., 2006). The system consists of amplifier, motor, lead screw coupling structure, ball screw with preloaded nut, workpiece and feedback sensors. The driver and motor system will lead the machining operation and the movement of the tool.

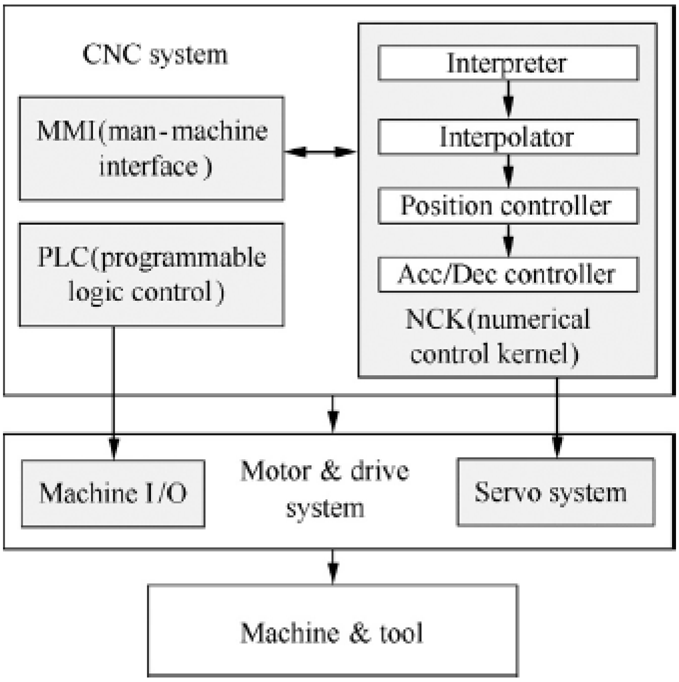

Figure 2-16 Traditional structure of CNC system(Wang et al., 2014)

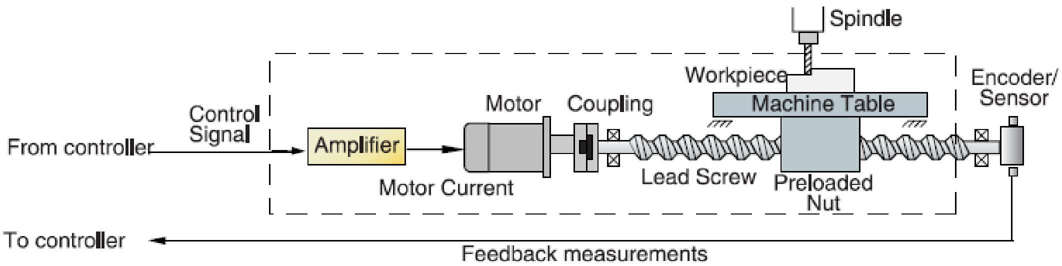

Figure 2-17 Typical ball screw drive system(Yeung et al., 2006)

The structure of milling machine is similar to the CNC machine, as Figure 2-18 shows (Altintas et al., 1990), the computer and the controller are connected by RS232, which is a standard serial port for transferring data or a signal. Currently, tool path is split into small segments as blocks. Each block contains NC block numbers, tool path information such as linear and circular, the position of the cutter, feed rate and other parameters (Yeung et al., 2006). Drip feeding is the name for describing the way tool path was transferred into CNC machine block by block. The reason of this was analysed in Chapter 2.6, the memory of CNC machine is too small for the whole programme package. The normal transfer speed of RS232 is 115200 bit/sec (Wikipedia, 2014). The transfer speed is another limitation of the study which requires the optimisation programme package need to be light-weight.

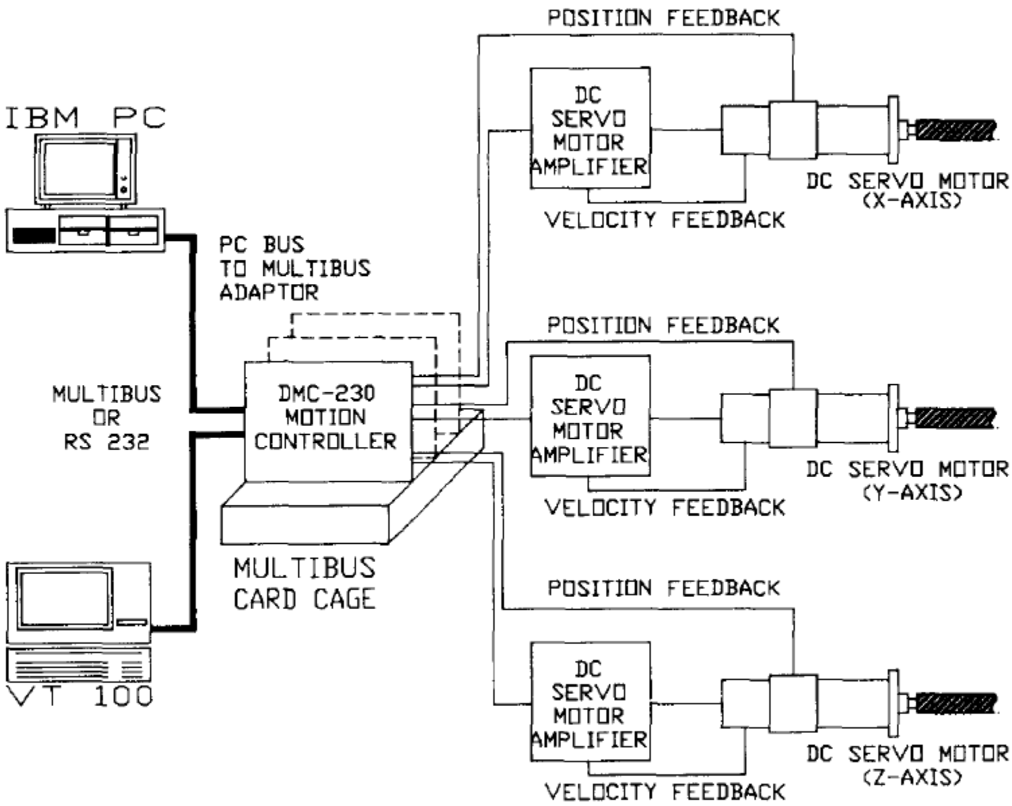

Figure 2-18 Mill machine system(Altintas et al., 1990)

2.8 Function block

2.8.1 Research and implement

Recently, emerging technologies such as function blocks (FBs) have been created and used for computer-aided process planning (Xu et al., 2011). These emerging technologies provide a new approach in the field of CAPP and make it possible for the high intelligence of CNC machines.

2.8.1.1 Overview

Function blocks are firstly introduced as an International Electrotechnical Commission (IEC) standard named IEC 61499-1 (International

Electrotechnical Commission, 2005) . FBs can be defined as basic FBs and composite FBs as Figure 2-19 shows(Wang and Shen, 2003).

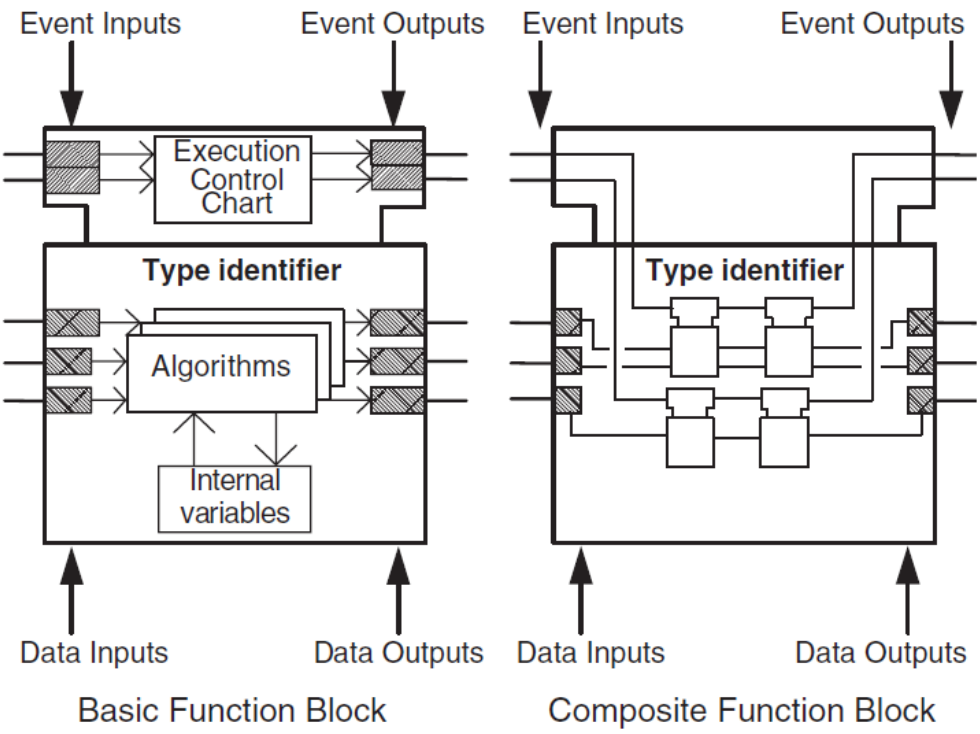

Figure 2-19 Basic and composite FBs

A basic function block is triggered by an input event combined with input data, and is controlled by an execution control chart (ECC). A single basic function block is able to generate multiple outputs based on the internal program and algorithm, which means that basic functions can produce different outputs even if the inputs are the same. Obviously, this property is very important for the implementation of automatic cutting parameter adjustments. A composite function block can be built by combining basic function blocks. One of the inside function blocks' output can be the input event of another function block.

2.8.1.2 Implementation in Machining

Wang (2003) first proposed using FBs for distributed process planning in machining. Later, in 2006, he introduced the specific design of FBs for fifteen classic machining features (Wang et al., 2006). Different FBs were developed for CAPP such as Meta FBs, Object FBs and Execution FBs.

FBs can also be used in assembly process planning, as the assembly features are recognised and distributed to the correct FBs. The first industrial implementation of FBs was reported in 2005, and since then, the role of FBs has been widely recognised within industry (Vyatkin, 2011). Recently, more and more research has focused on this field. Different kinds of FBs were developed for various purposes such as machining feature function blocks (MF-FB).

2.8.2 Software tools

Different kinds of tools were developed for the design and implementation of FBs; Function Block Development Kit (FBDK), Framework for Distributed Industrial Automation and Control (4DIAC), workbench, nxtSTUDIO and ISaGRAF. Among these tools, FBDK is the most popular for IEC-61499-compliant system development (Wang et al., 2009).

2.8.3 Advantages and disadvantages of FBs

FBs can realise real-time dynamic distributed decision making in industry (Wang et al., 2012). With real-time monitored signal as the input data, high speed algorithm or logic can make quick decisions and then with the output of that decision, a real-time monitoring and control or optimisation system can be built easily. As Wang et al, (2012) stated, CNC machines can gain extra intelligence and a high level of automation with the implementation of FBs.

It is obvious that the main advantages of FBs are: they are suitable for real-time monitoring and control, especially for real-time parameter control, and they provide extra intelligence and automation for CNC machines. Furthermore, because FBs belong to emerging technologies, this means that the real-time system will depend on the CNC machine resource, unlike other systems needing an independent system. However, emerging technologies also carry drawbacks; the majority of the resources of CNC machines will be used to maintain the operation process. The size of FBs will be restricted by the limited resource.

2.9 Research gap analysis

Off-line parameter optimisation has attracted much research over the past 30 years, and over 20,000 papers can be found on the subject. Compared to the popularity of off-line optimisation, research in on-line optimisation is still in its early stage. Relevant searches only show approximately 5,000 results; among these, a real case for implementation of real-time optimisation in real-life can barely be found.

The development of machining in the past century shows that almost all machining processes are slowly on their way to high automation and high intelligence. Real-time control and optimisation is the key of CNC machines in realising this. Emerging technologies such as FBs provide a new approach to deal with on-line optimisation and control.

So far, by using the keywords and websites introduced in Chapter 2.3, almost no paper can be found in the field of using FBs to do on-line optimisation or control. This paper marks a new attempt to implement FBs on on-line parameter optimisation and control.

However, the research aims and objectives have to comprise when limited by time and speed. The expected running time of a programme is within 50ms which means the programme has to run very fast. In that case a simple and fast optimisation method such as HC is more suitable for the research than other methods mentioned above. Based on the feature of HC, feed rate was chosen as the only variable parameter of the optimisation programme.

2.10 Conclusion

The literature review shows that the top three factors of both off-line and on-line optimisation are feed, cutting speed and depth of cut while the objectives are to reduce production time and cost, and stabilise cutting force. Following a questionnaire to industry to confirm the factors and objectives that are of the most interest to them, the research slope can be narrowed down.

The research on current CNC controllers in the market shows that the leaders of the business are slowly on their way to adaptive control, and new models can realise a simple on-line control of the feed rate based on the real-time monitoring signal of tool load or spindle load. The change and movement within these companies illustrates the future development and custom demands.

The study on FBs makes it clear that FBs are suitable for real-time monitoring and control, which could meet the future development of CNC controllers. Considering current adaptive controls of CNC controllers and the objection function of cutting force, it is suitable for building a cutting force based feed rate optimisation system.

The aim of this paper is to build a real-time optimisation system based on FBs. The system should use real-time monitoring cutting force signal as the input, following which a light-weight programme framework inside FBs will calculate and output the optimised feed rate.

2.11 Summary

In current real-life machining processes, the tool path and parameters such as feed rate and cutting speed are pre-set and generated in form of G-code [ISO 6983, settled by the Electronic Industries Alliance in the early 1960s]. Once the G-code is uploaded into the CNC controller, the tool path cannot be changed and the feed rate can only be adjusted manually based on the experience of the human expert. Some advanced CNC controllers can realise automatic adjustment of the feed rate, but the principle of the control is similar to the manual operation.

Thus, the problems are:

- The adjustments of the human experts are limited by their experience.
- The adjustments of the human experts are based on their senses, and in most cases these modifications cannot be called optimisation.
- Advanced CNC controllers can carry out minor real-time adjustments and control but hardly realise real-time optimisation.

The ideal situation of machining process is the CNC controller real-time monitoring the signals such as cutting force, spindle load, tool vibration and the inside algorithms will optimise the cutting parameters such as feed rate, cutting speed, spindle speed and depth of cut based on the input signals. The parameters optimised in real-time will be most suitable setup for machining process.

In this Chapter, six sections were covered: basic knowledge of milling, optimisation in milling, optimisation methods, optimisation objective functions, current CNC controllers and FBs. The structure followed the process of study in order to provide useful information such as; lists of theses of off-line and on-line optimisation, the top three to five popular factors and objectives from studies in recent years, current development of CNC controllers and a list of famous CNC controllers for later research.

3 Methodology

3.1 Introduction

The methodology is very important in a research study, as it will determine the process of the study and bring a clear logic map to the researcher. The whole research process will be guided by the logic map, which can guarantee the quality of the study.

In this paper, the framework of the research can be delivered through three questions as Figure 3-1 shows. The first question is; how can the research aims and objectives be confirmed? This is a question that all researchers need to answer, and the answer for this paper is through literature review and questionnaire. The second question is: how can the system be built? The correct optimisation method must be found and programmed using Java language which could run in FBs. The third question is; how can this be validated? This is also a question that most researchers need to answer. Two stages, self-testing and case study are used in this paper.

Question	**Methodology**	**Deliverables**
Question 1: How to confirm research aim and objectives	Literature review Questionnaire	Literature review report Questionnaire analyze report
Question 2: How to build the system	Create Java programme which could build relationship between factors and objectives	Cutting force model based system
Question 3: How to validate	Self-testing Case study	Final report

Figure 3-1 basic framework of methodology

3.2 Question 1

Four sub-questions are contained within question 1, and following these questions can confirm the aims and objectives step by step. Figure 3-2 shows further details of the four questions.

Firstly, the most basic question is asked; what factors can be optimised in milling? To answer this, a basic knowledge of milling needs to be gathered and basic factors of the milling process can be delivered. The second question is; among those basic factors, which are the most popular within the research area and industry? The result can be gathered from previous thesis from recent years. By analysing these thesis, and combining the result with that from the questionnaire, the top three to five most common factors and objectives can be revealed.

The last step is to confirm the factors and objectives of this paper. A review of previous literature on CNC controllers will assist in finding out what industry has already done in this field, and a review on literature on FBs will help to discover the properties of it and its advantages. Then, when combining all this information, the factors and objectives of this paper can be confirmed.

Sub-question	Methodology	Deliverables
Sub-question 1: What are the factors can be optimized in milling	Literature on milling	Basic factors of milling process
Sub-question 2: which factors worth to be optimized most	Literature on off-line and on-line optimisation Questionnaire	Key factors and objectives in research and industry
Sub-question 3: How to confirm the factors and objectives suitable this paper	Literature on current CNC controller, FBs	Factor and objectives of this paper

Figure 3-2 Sub-questions for question 1

3.3 Question 2

The creation of a real-time optimisation system was followed by 3 steps as Figure 3-3 shows.

First of all, a suitable optimisation method must be found. Through a literature review, basic optimisation methods were easy to gather. Simultaneously, suitable objective functions need to be confirmed. The advantages and disadvantages of each method, together with the properties of the objective function, will determine the most appropriate optimisation method.

The final question is; how can the method and objective functions be combined? This can be carried out through computer programming. Tools such as Java and Matlab can be used for this purpose. Java was chosen considering that FBs also run and support Java.

Sub-question	Methodology	Deliverables
Sub-question 1: How to optimize the factor	Literature on optimisation methods	Basic optimisation methods
Sub-question 2: How to build the relationship between factor and objective	Literature on objection function	Objective function: cutting force function
Sub-question 3: How to combine the method and objective function	Java programme	Cutting force model based system which can adjust feed rate or cutting speed according to the cutting force value

Figure 3-3 Sub-questions for question 2

3.4 Question 3

Validation of a real-time system, especially for a milling operation, is difficult. It is well known that milling processes are complex due to the influence of multiple factors such as cutting force, spindle load and vibration. Simulation is the only method available for this research. The ideal method of validation is through experiments, which the machine can feed back into the real cutting force value based on the adjustment of the feed rate or cutting speed. However, by simulation, real cutting force values cannot be obtained. Calculation is the only way to evaluate the cutting force value based on an ideal situation in which cutting force is the only factor to influence the cutting process.

Lacking real cutting force value feedback, it is hard to know how long the cutting force will maintain after the adjustment of the feed rate or cutting speed. The cutting force can be stabilised in a certain zone of value but how long the stabilisation will last will be a problem. Fig.3-4 shows the typical cutting force curve (Adolfsson et al, 1995), the blue line shows the real cutting force value based on measurements and the yellow dashed line shows the expected cutting force value. The validation is to adjust the feed rate or cutting speed in order to make the blue line closer to the yellow dashed line.

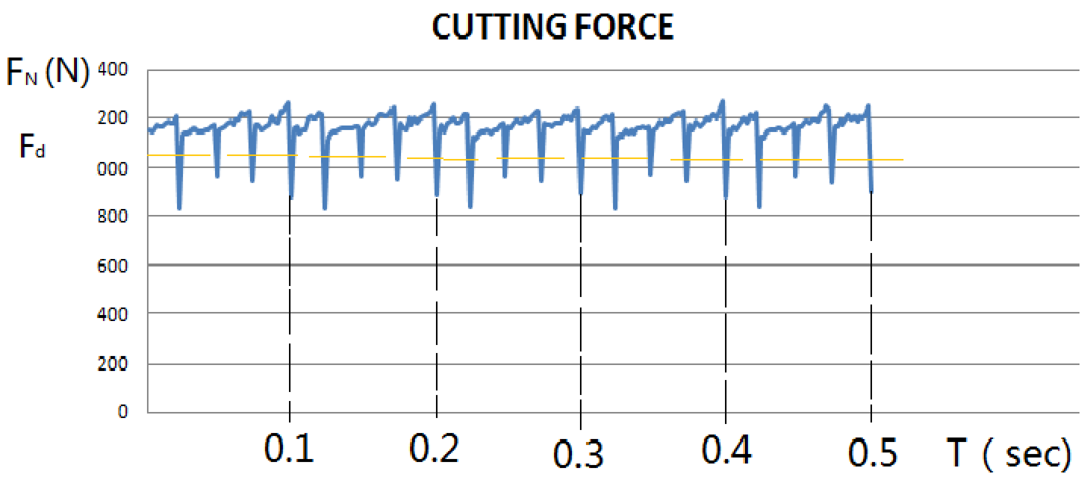

Figure 3-4 Typical cutting force curve (face milling)

3.5 Summary

In this chapter, the research methodology was presented in the form of questions. This research could carry on step by step by asking and answering the questions. In the meantime, the methodology was supported by the literature review and the logic map of the literature review, followed by the logic map of the methodology. Each decision made during the methodology was supported by the literature review. Finally, the aims and objectives of this paper were supported by the literature review and the methodology.

4 Data collection and analysis

4.1 Introduction

Usually, data collection is important to researchers because most studies are faced with real-life problems which need data input and feedback. Many methods can be applied to collect information such as questionnaires and interviews. In this paper, the questionnaire method is adopted.

A questionnaire is one of the most important methods in collecting information; the main purpose is to allow researchers obtain real and accurate data by asking the right questions of the right person (Hague, 1993).

From the literature review, the most common factors and objectives in similar research were analysed. The questionnaire is designed to collect information on the factors and objectives of the milling process in real-life. The result will be analysed and compared to the literature review to find out if they share the same interests. In order to collect accurate information, the questionnaire was sent to COMAC (China), Prodintec (Spain), and Powerkut (UK).

The questionnaire included 14 questions. The first section contains 4 general information questions such as the participant's role and experience in the field. The second section contains 10 questions based on the factors, objectives and optimisation in milling. Table 3-1 shows the list of interviewees; 4 experts took part. The questionnaire and results of the interviews are recorded in Appendix D,E,F..

Table 3-1 List of interviewees

Role	Number	Experience
engineer	1	1-3 years
R&D	3	5-15 years

4.2 Analysis

Two questions were designed to collect information on the most important factors in milling processes (see Figure 4-1). The first question is to find out which factors influence the tool path the most. The second is to discover which factors need to be adjusted the most.

Q3. What are the parameters you usually change, from the values given by the tool maker, in order to achieve a good toolpath with respect to the above mentioned objectives?

Parameter	1 (rarely)	2	3	4	5 (usually)
Feed rate					
Cutting speed					
Depth of cut					
Tool path pattern					
Width of cut					
Coolant					
Other					

Q4. What parameters do you usually fine tune on the controller of the machine?

A. Feed rate
B. Cutting speed
C. Coolant
D. Other: ______________________________

Figure 4-1 Questions on factors

Figure 4-2 shows the results of these two questions. For the first question, the top three answers were federate, cutting speed and depth of cut, which were exactly the same within the literature review. This result indicates that the researchers and companies share the same interest in these factors. The result of the second question shows that in real-life operations, feed rate needs to be adjusted manually in most cases. Knowledge of this will assist in confirming the factors of this paper for the real-time control and optimisation system. Applying FBs in real-time control and optimisation system will give the CNC machine extra intelligence and a higher level of automation, which will reduce the level of manual operation.

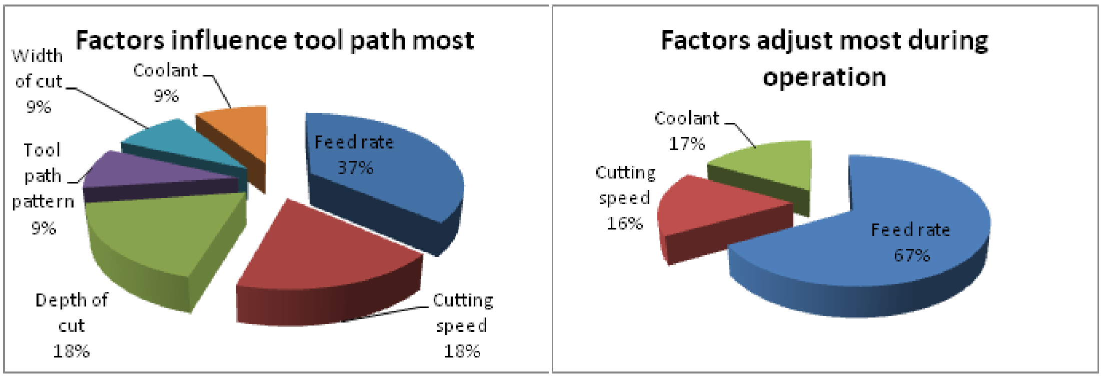

Figure 4-2 Results of questions on factors

Figure 4-3 shows the questions designed to decipher the most important objectives in the milling process. The first listed the most common objectives expected for the minimisation of air cuts, which has rarely been found in research. The second question is designed to understand how to build the relationship between factors and objectives in real-life.

Q1. When creating a tool path what are the main objectives you consider? (choose all that apply)

A. Minimum air cuts
B. Minimum time
C. Minimum tool wear
D. Maximum material removal rate
E. Minimum surface roughness
F. Maximum production rate
G. Minimum power consumption
H. Other: ______________________

Q5. How do your machine tool operators usually monitor the machining process?
A. Sound
B. Vibration of the machine
C. Spindle load
D. Load on the axes
E. Power consumption
F. Cutting forces
G. Temperature of the work piece / tool
H. Other: ______________________

Figure 4-3 Questions on objectives

The results of the two questions, as Figure 4-4 shows, are that the most popular objectives differ from the literature. The main objective is to minimise air cuts, which, as previously stated, is rarely found in the literature review. Minimisation of production time, tool wear and surface roughness follow minimising air cuts. These objectives are also in the same order within literature review. The result of second question shows how operators make decisions to adjust the parameters. The result might be more suitable for expert systems which are based on the experience of human experts to control and optimise. The answers from of this question are based on the current situation. Most of the CNC machines do not have real-time monitoring systems, which will show the current data such as cutting force, power and load. Experienced experts still need to make decisions based on their feelings such as sound and vibration.

Based on the data collection on CNC controllers, most of the new CNC machines are capable of providing the real-time signals of cutting parameters such as cutting force, power, load, feed rate, cutting speed and spindle speed.

The future real-time system, to some extent, will be built based on these specific signals.

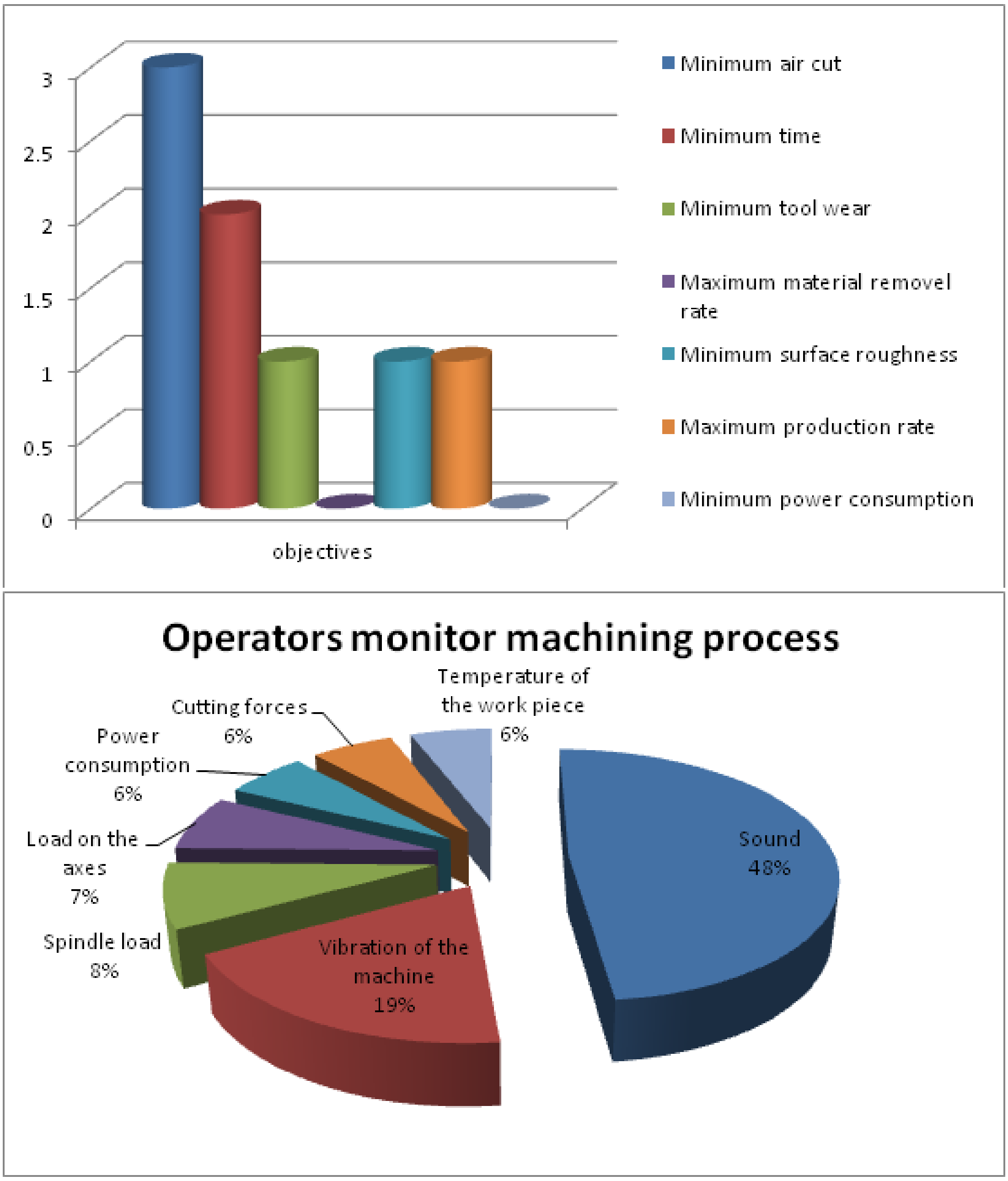

Figure 4-4 Result of questions on objectives

4.3 Summary

This chapter provides the results of the questionnaires regarding the factors and objectives in machining considering real-life demands. The factors from the questionnaire are the same as within the literature review, meaning that currently, the researchers and the companies are still interested in the optimisation of these factors. Furthermore, the result also shows that in spite of heavy research on the optimisation of the factors, there is still space for further improvement in the field as the research has not satisfactorily met the requirements of the industry. The results of the questionnaires regarding “milling objectives” are similar to results observed within the literature. Industry is more interested in time, cost and quality. The results also reflect that human operations are still required and necessary in real-life. The adjustment of the parameters will depend on the experience of human experts. This means that there is a vast area for research in the field of real-time optimisation and control systems.

5 System development

5.1 Introduction

The development of a real-time optimisation system is discussed within this Chapter. As Figure 5-1 shows, system architecture, cutting force model, chip thickness, and initial and final models will be introduced in detail .

System architecture will introduce the concept of a cloud system based on FBs, and data acquisition, data analysis and optimisation algorithms will be discussed. Cutting force model and chip thickness are the core of the real-time optimisation system; therefore, detailed objective functions and the unformed chip thickness will be introduced. The initial model will discuss the single pace HC method and the final model will discuss the adaptive hill climbing (AHC) method.

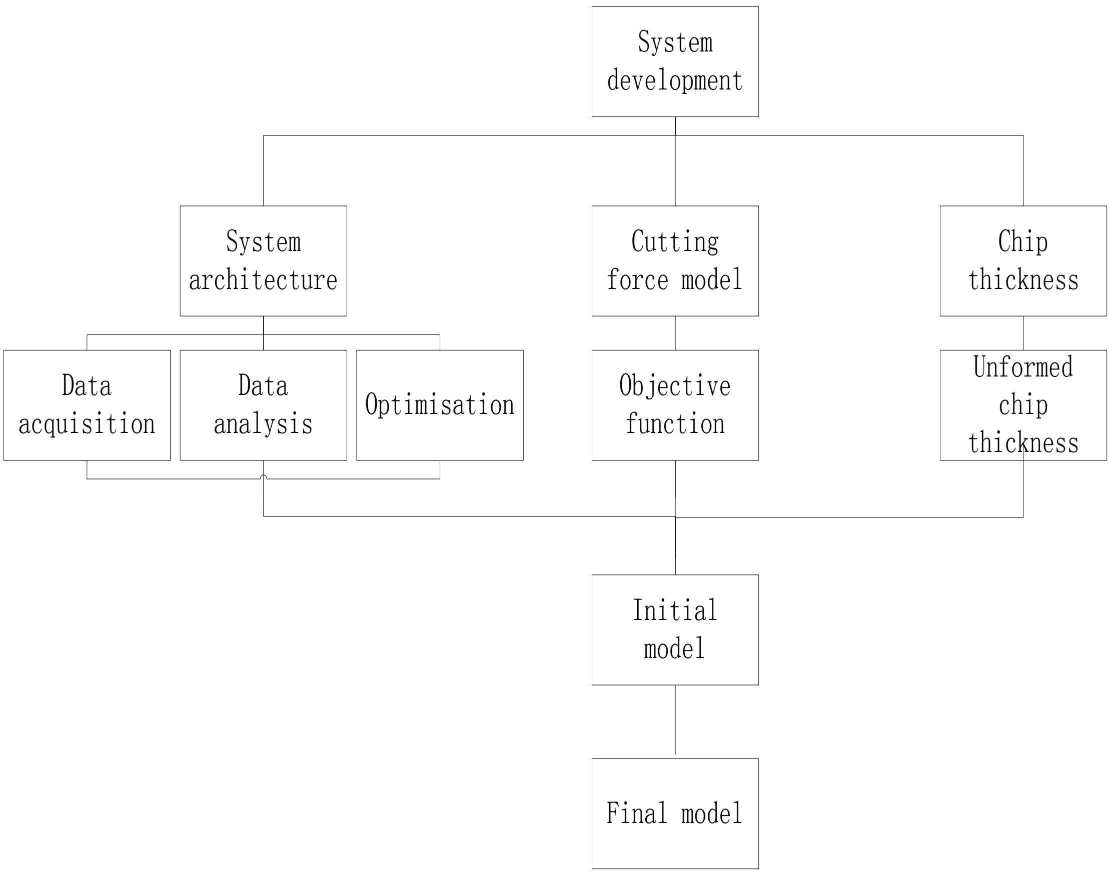

Figure 5-1 The structure of system development

5.2 System architecture

Applying FBs in computer process planning for milling operations is currently being developed through the EU project CAPP-4-SMEs. The FBs based system is being developed in a Cloud environment. Tapoglou et al.(2014) proposed a FBs and Cloud based on-line tool path optimisation system, as Figure 5-2 shows. Four sections, including Data acquisition, Data analysis, Optimisation and Visualisation interface are introduced into the system.

In this paper, the proposed system is similar to the one introduced earlier. The difference is that the system in this paper has no independent data analysis section, therefore the signals are analysed within the parameter optimisation section. Separately, the structure of the system is exactly like the system in Figure 5-2, which might currently be the typical structure of FBs and Cloud based on-line optimisation systems.

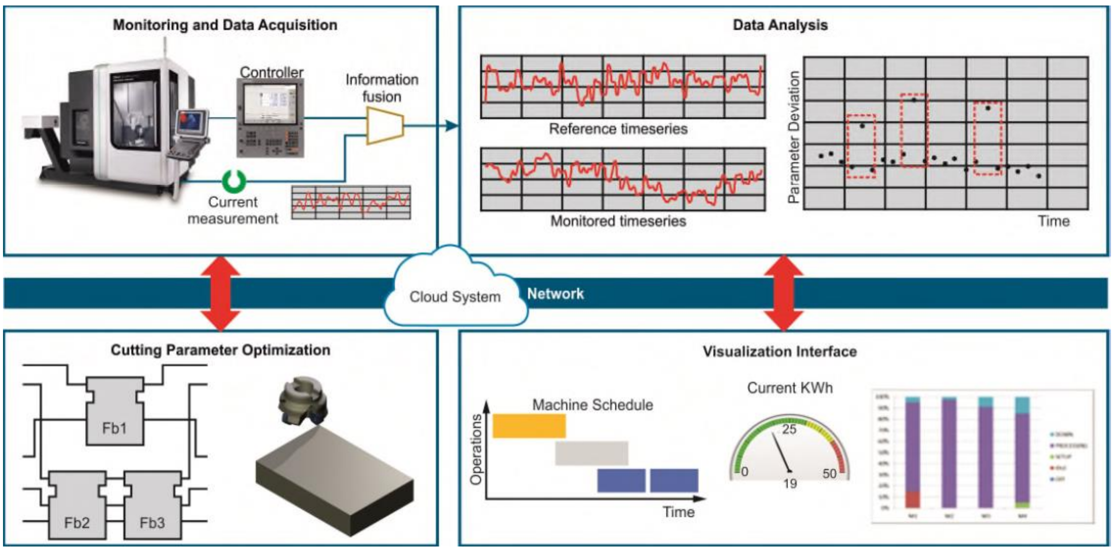

Figure 5-2 FBs and Cloud based system

5.2.1 Data acquisition

Data acquisition is very important within the system because the core of the system is to compare the input cutting force signal with the reference or ideal cutting force. Thus, the input cutting force signal is crucial to the system.

Adolfsson et al. (1995) proposed a real-time cutting force measuring system for face milling operation. The proposed system applied sensor elements on the cutting tool which will reduce the loss of information due to the short distance between the cutting edge and the sensor. Strain gauges were used due to the good behaviour of frequency and temperature as well as the ability to provide a continuous signal. The system can provide a maximum sample rate of 4800 Hz (1 sample/second (1Hz)).

Simultaneously, the current signal of feed rate and cutting speed measurements will be input into the system for the calculation of unformed chip thickness and theoretical cutting force value.

5.2.2 Data analysis

Normally, complex FBs and Cloud based on-line optimisation or control systems will need an independent data analysis section, as Figure 5-2 shows. The FBs based system will be mostly used for dynamic and adaptive control, which is effective when dealing with uncertain situations such as tool breakage and unexpected cutting force overload. Different kinds of uncertain situations will be setup in the FBs and input data will be analysed to ascertain which uncertainty the current input is. Each uncertainty will be conducted using a certain solution.

As mentioned in Chapter 5.2, the proposed system in this paper has no independent data analysis section because the only uncertainty in this paper is the cutting force overload. The cutting force overload will be recognised by the comparison with the reference value, and then optimised by the optimisation algorithm.

5.2.3 Optimisation

All the data collected will be transferred into optimisation FBs as inputs. The optimisation FBs will decide which data needs to be calculated and the Hz of the input data. Figure 5-3 shows the structure of the optimisation section. Tapoglou et al.(2014) proposed the structure of the layer as one of the most typical FBs and Cloud based optimisation structures. This paper will also adopt this structure of layers. Tool data will be received from the CNC machine such as cutting force, feed rate and cutting speed. Featured data, such as the geometry of the workpiece, depth of cut and width of cut are transferred to the FBs through the Cloud network. All of the necessary data will be combined and put into the optimisation FBs. The optimisation algorithm inside the optimisation FBs will run based on the input data and output the optimised value of parameters. The output value will be translated into machine specific G-code because there is currently almost no protocol for running FBs on a CNC machine.

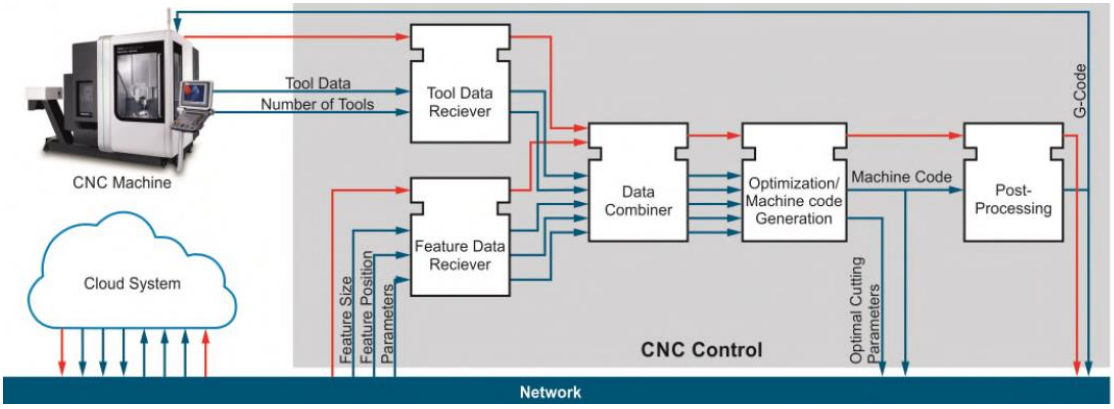

Figure 5-3 Structure of the optimisation software

5.2.4 Visualization interface

The real-time FBs and Cloud based optimisation system runs together with the visualisation interface which is specially designed for the system. The visualisation interface was designed by Qi Qiao, MSc by research student at Cranfield University. The visualisation interface is capable of presenting the simulation of the machining process in real-time, as Figure 5-4 shows. The tool path is displayed in a 3D model. The current machining parameters such as feed rate and cutting speed are presented, as well as the current position of the cutter.

Furthermore, the visualisation interface is designed to display the current curve of the cutting force and the reference cutting force curve, the real feed rate curve, spindle speed curve and spindle speed curve of the machining process. These curves will help engineers to analyse the machining process for further optimisation. The functions of this section are still in development.

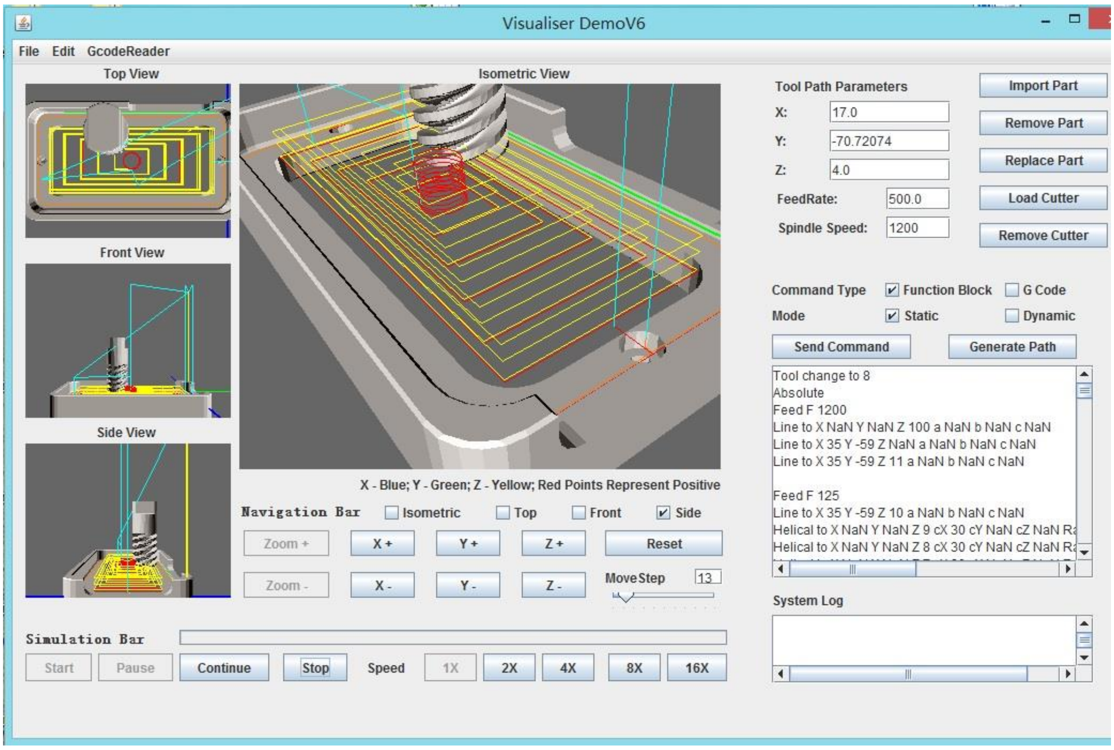

Figure 5-4 Visualisation interface

5.3 Chip thickness

As mentioned in the previous Chapter, chip thickness is the key to building a relationship between feed rate, cutting speed and cutting force. The chip thickness is different according to the depth of the cut, cutting tool, touching angle σ , feed rate and cutting speed which makes it more complex. In this Chapter, different situations will be discussed.

In face milling processes, normally two kinds of situations occur; the depth of cut is bigger than the radius of the cutter, and the depth of cut is smaller than the radius of the cutter. In the first situation, as Figure 5-5 shows, the depth of cut d is bigger than the radius of the cutter (the shape of the chip is shown as the shadow), the value of chip thickness increases as the cutter rotation angle $\emptyset_i$ changes, the biggest chip thickness appears when $\emptyset_i$ equals $\pi/2$ and following that, the value of chip thickness will decrease until $\emptyset_i$ equals the touching angle σ.

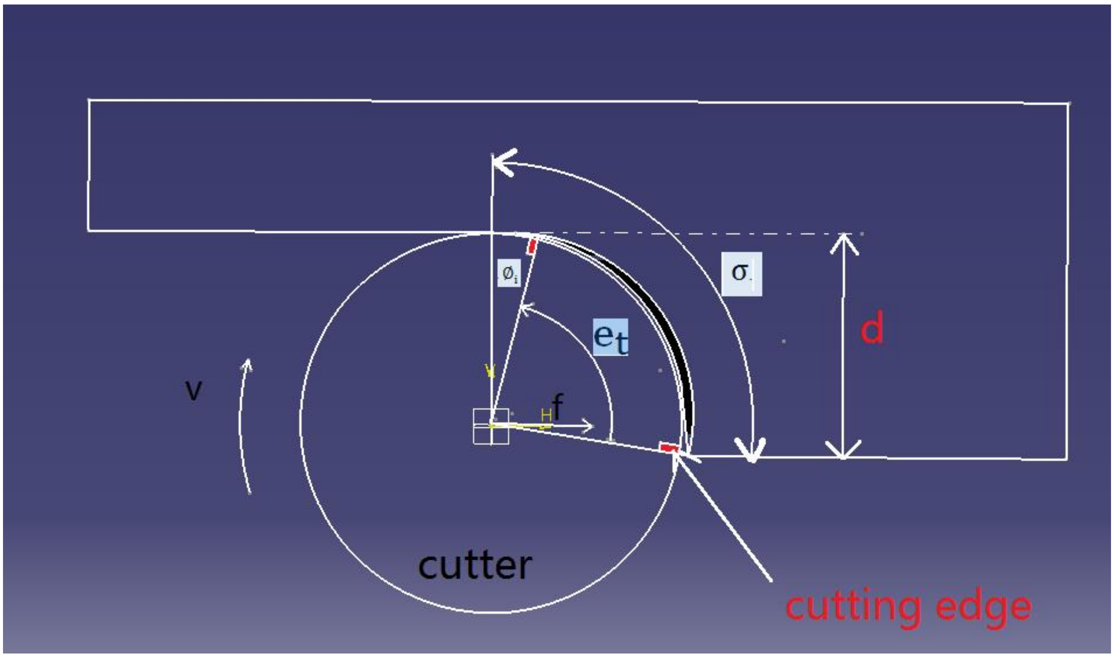

Figure 5-5 Cutting model when d>=D/2

The maximum cutting force F_{max} is dependent on the number of cutting edges in the area of σ. The angle between two cutting edges can be calculated as :

$$\alpha = \frac{2\pi}{z} \tag{15}$$

If α is smaller than σ, then at least two cutting edges work at the same time in the area of σ. F_{max} is the sum of F for each cutting edge. Thus, the number of cutting edges working at the same time is very important for the calculation of F_{max}.

The value of changes to chip thickness basically follows the value of sin function, as Eq. 11 shows, and the formula can be written as simply as:

$$h_{li} = X \sin \emptyset_i \tag{16}$$

X is regarded as a constant, and F_{max} is dependent on the number of cutting edges that work at the same time. The following Figures show the relationship between the number of cutting edges and F_{max}. The touching angles σ of 100, 120 and 150 were chosen to gain the general rule of the relationship.

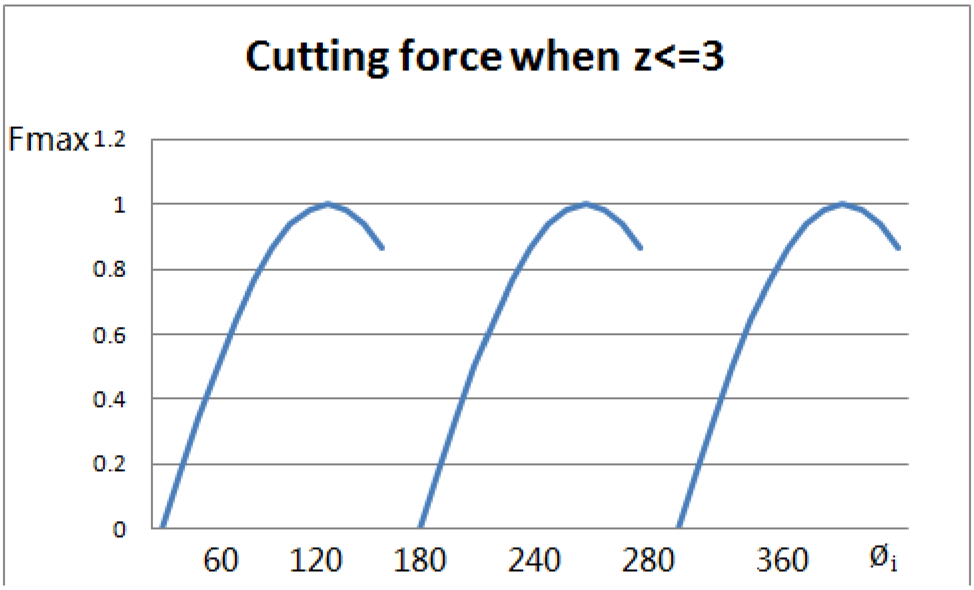

Figure 5-6 Cutting force model 1 when z<=3

Figure 5-6 shows that when z<=3, only one cutting edge will work in the area of σ. F_{max} appears when $\emptyset_i = \pi/2$. F_{max} is expressed as:

$$F_{max} \approx C_r \frac{f \cdot e_t}{v} (\sin \pi/2) \cdot b \qquad (17)$$

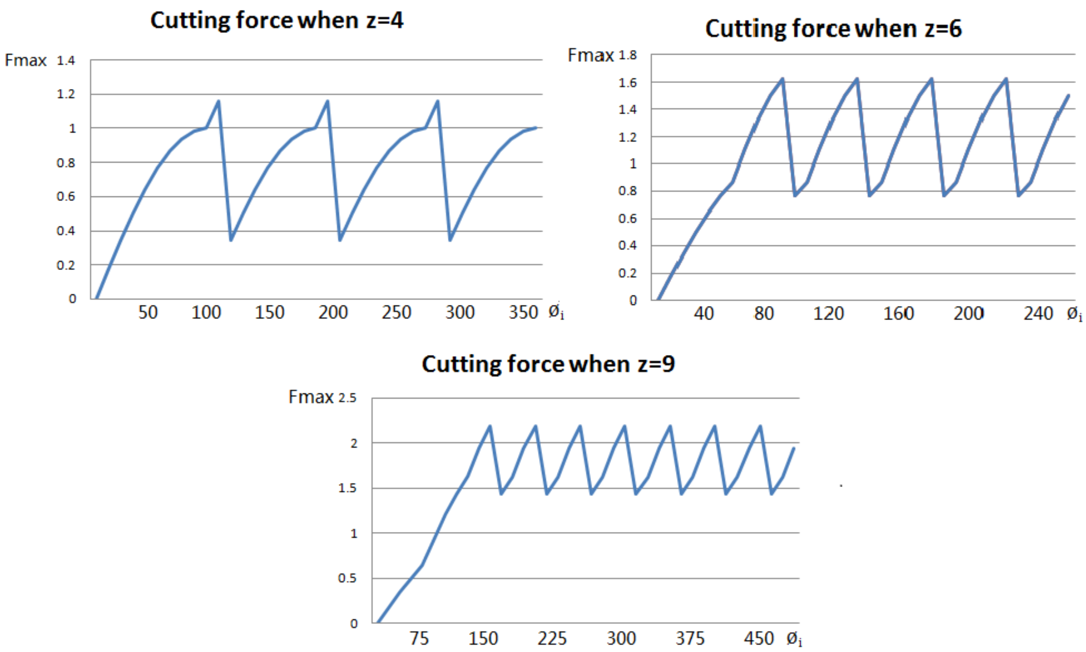

Figure 5-7 Cutting force model 1 when 4<=z<=9 and 90° <=σ< 110°

When 4<=z<=9, the value of chip thickness is different according to the value of σ. Roughly, when 90° <= σ <110° , the value of F_{max} is shown as in Figure 5-7. Based on the rule of the value, F_{max} can be calculated as:

$$F_{max} \approx 0.2(z+1)C_r \frac{f \cdot e_t}{v} (\sin \pi/2) \cdot b \tag{18}$$

In another situation, such as Figure 5-8 shows, when σ>=110° , the value of F_{max} can be expressed as:

$$F_{max} \approx 0.2(z+4)C_r \frac{f \cdot e_t}{v} (\sin \pi/2) \cdot b \tag{19}$$

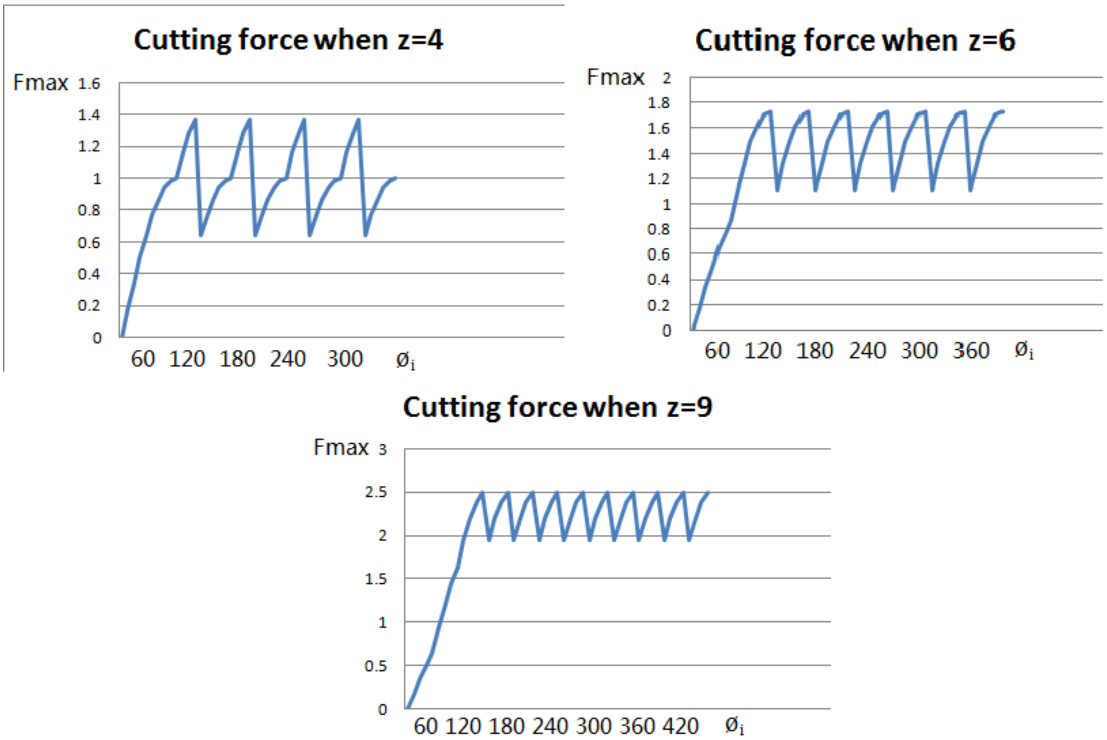

Figure 5-8 Cutting force model 1 when 4<=z<=9 and σ>=110°

Figure 5-8 shows the value of F_{max} when σ>=110° and z>=4, and the result shows that the rule of F_{max} follows the same as is shown in Eq.19.

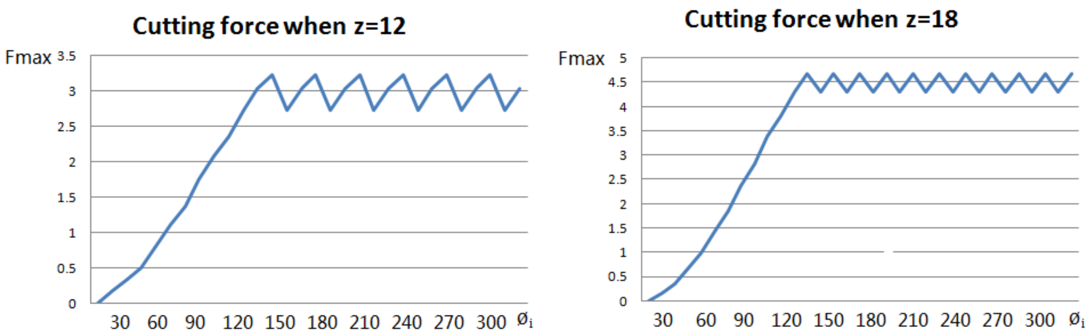

Figure 5-9 Cutting force model 1 when z>=4

In the second situation, when the depth of cut d is smaller than the radius of the cutter, as Figure 5-10 shows, the value of F_{max} increases when the cutter rotation angle increases and the largest value appears when $\emptyset_i$ equals the touching angle σ and, then the value of F_{max}=0 for only one cutting edge in the area of σ. Similarly to the first situation, F_{max} depends on the number of cutting edges that work at the same time in the area of σ.

If only one cutting edge works, F_{max} can be calculated as:

$$F_{max} \approx C_r \frac{f \cdot e_t}{v} \sin \sigma \cdot b \tag{20}$$

$$\sigma = \cos^{-1} \frac{d - D/2}{D/2} \tag{21}$$

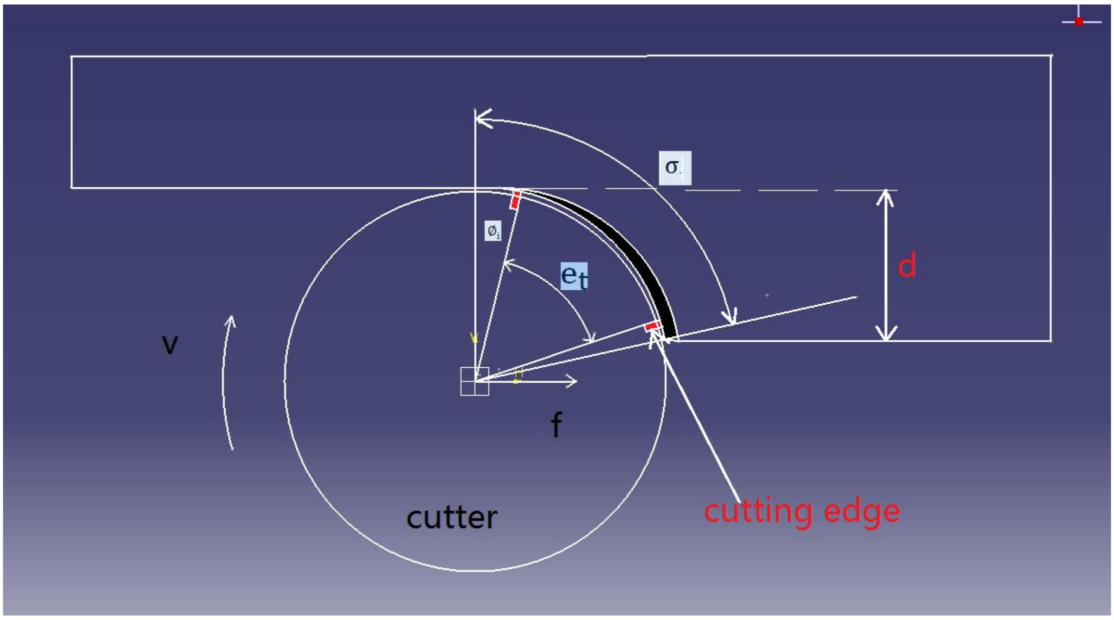

Figure 5-10 Cutting model when d<D/2

When z<=4, only one cutting edge works in the area of σ , the value of F_{max} is as shown in Figure 5- 11 and can be calculated using Eq.20.

When z>=5, at least two cutting edges work at the same time, the value of F_{max} equals the sum of the cutting force of each cutting edge. Figure 5-12 shows the rule of changes to F_{max} according to a different number of cutting edges and F_{max} can be expressed as:

$$F_{max} \approx 0.2 \cdot z \cdot C_r \frac{f \cdot e_t}{v} \sin \sigma \cdot b \tag{22}$$

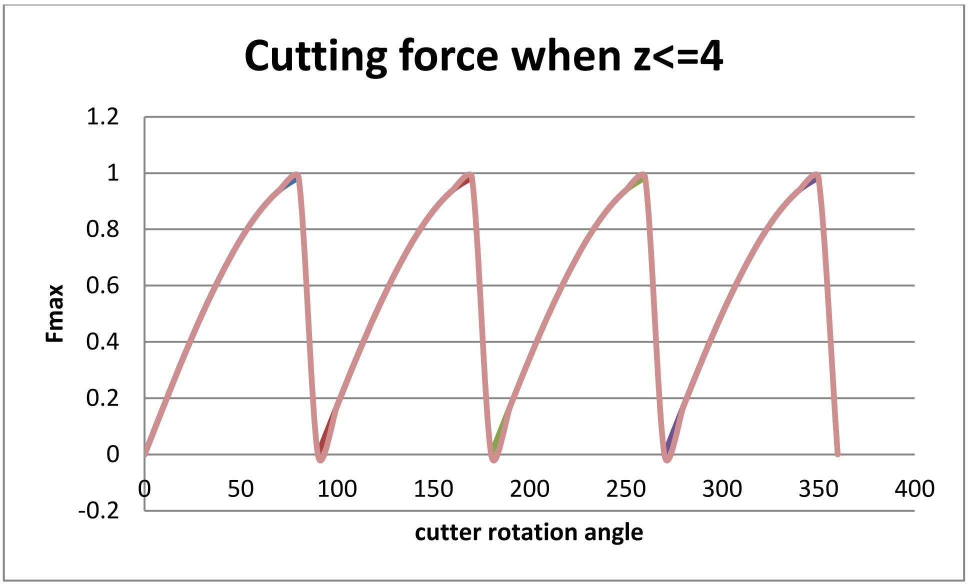

Figure 5-11 Cutting model 2 z<=4

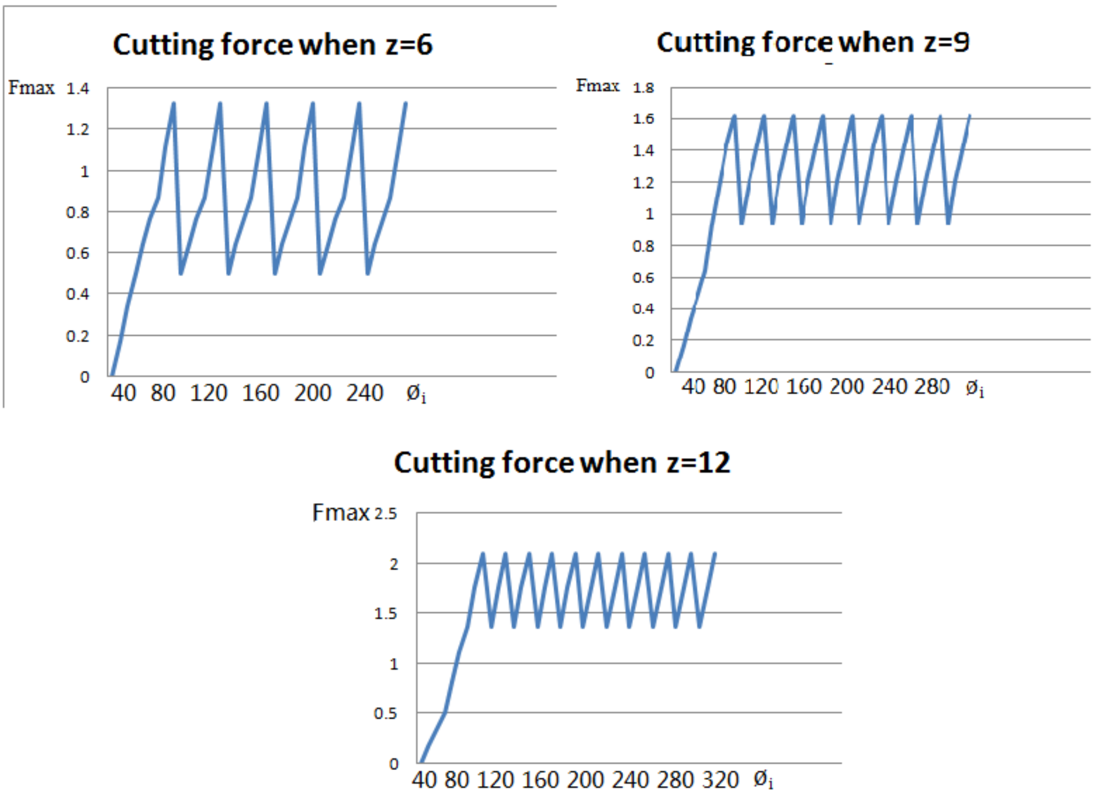

Figure 5-12 Cutting model 2 z>=5

In general, the many different kinds of situations of chip thickness and the value of F_{max} based on this can be summed up as shown Figure 5-13. Two large types and 5 smaller types of situations are discussed. The value of F_{max}

is calculated by approximation in order to gain a simple mathematical model which will benefit the speed of the calculation.

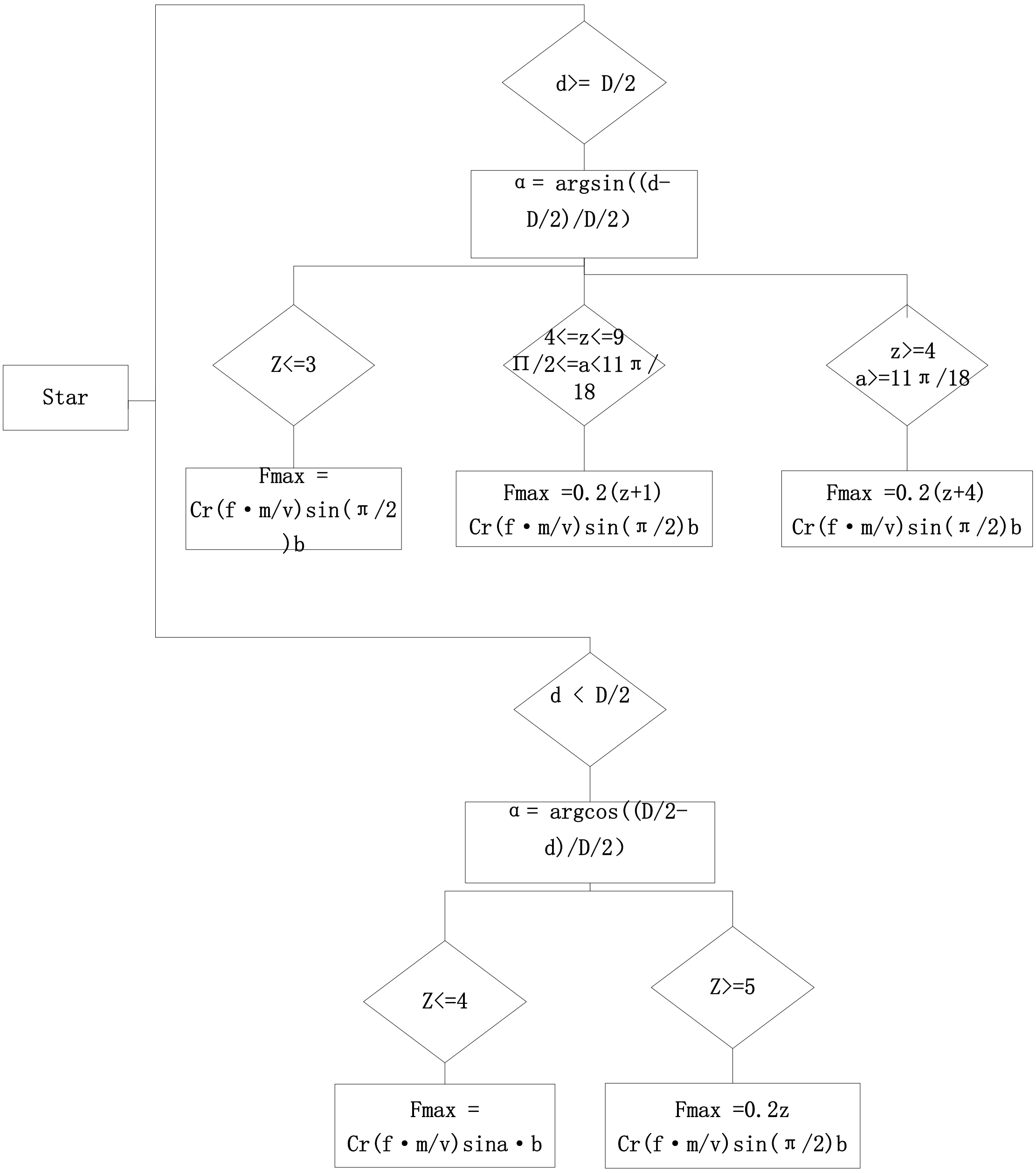

Figure 5-13 Objective functions to calculate total cutting force

5.4 Initial model

The initial idea behind the system is simple; the basic function is to optimise feed rate according to the input value of F. If the monitored cutting force F is larger than the reference value Fd, the feed rate will be reduced by △f until it finds the optimised value. In another situation, when F is smaller than Fd, the feed rate will increase by △f. The final situation is when F equals Fd, which might be very rare, and the system will do nothing.

This initial system reflects the basic idea of how the system should work; the basic testing shows many problems:

- One static △f can easily cause a lack of an optimum value. If △f is too big, step over will happen. On the contrary, if △f is too small, the calculation time will increase.
- The value of F is important when F is close to Fd, with one static △f bringing step over and lacking the optimum.
- Normally, in a real-life operation, feed rate cannot be adjusted without limitations; the minimum and maximum values of feed rate must be given, and the optimisation should be limited by the boundary. Thus, when the adjustment of feed rate is beyond the boundary, a second parameter should be considered.
- The constraint should be more complete, otherwise when step over occurs, the system will run for a long time to finish the calculation, which is far from the optimum.

In order to solve the problems, the system needs to be more powerful. △f needs to be adaptive according to the value of F, the input value of F needs to be located more precisely, and a second parameter needs to be considered when feed rate is beyond the boundary. As the problems were solved one by one, the final model of the system was determined.

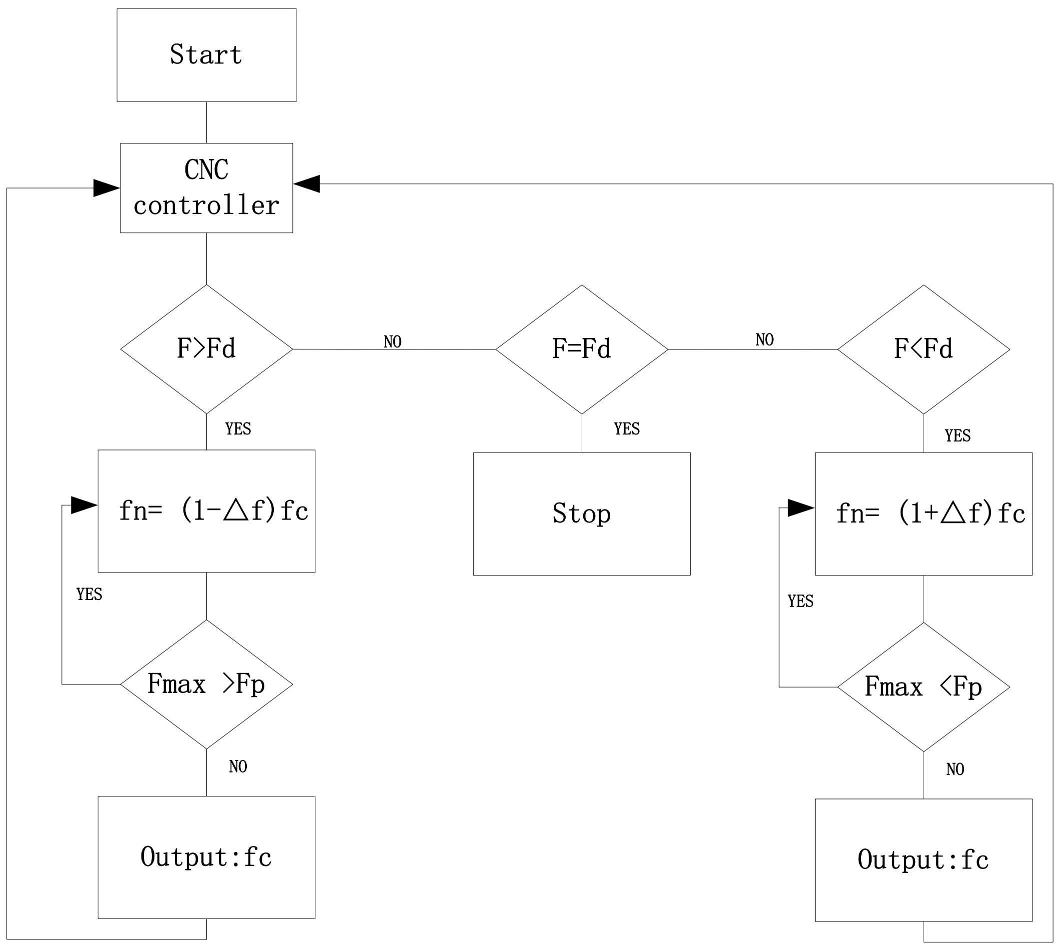

Figure 5-16 Initial model with one variable

5.5 Final model

Figure 5-17 and Figure 5-18 show the logic of the final model. The logic can be explained through seven steps. The basic logic of F>Fd and F<Fd are similar, and the following steps only explain the logic when F>Fd, as Figure 5-17 shows.

Step one: the system will choose the F_{max} function based on the input parameters, as Figure 5-15 shows.

Step two: after the first judgement of the value of F, three situations occur; F>Fd, F=Fd, and F<Fd. After the comparison of the F, the system will decide the next step. Figure 5-17 shows the logic of F>Fd, Figure 5-18 shows the logic of F<Fd. When F=Fd, the system will not work.

Step three: four criteria are applied to decide and locate the value of F; this kind of setup is to prevent step over occuring. For example, if Fd=500 when F=520, after the first decrease of △f, the next value of F will be less than 500 and will not meet the optimum. By using the criteria, F =1.04 Fd , thus △f=1/50△f, and with this kind of △f, the next value of F will definitely be located in the area of (0.98Fd, 1.04Fd), therefore, the optimum can be achieved.

Step four: the four criteria will decide which steps the value of F goes through next. If F>1.1Fd, F goes to the first loop. In the first loop, △f is set equal to 10%. After the first △f, the criteria $f_{min} \leq f_n \leq f_{max}$ will compare if the next value of feed rate is out of the boundary. "YES" means the f_n is inside the boundary and the next criteria uses the golden ratio to fast approach Fd. When the result is "NO", the loop starts again and when the result is "YES", three more criteria will apply to decide where the current value F as F_{max} goes to next. This step up is the same as with step three; the purpose is to make sure step over will not occur and the system will not fall short of the optimum. Three criteria will assign the F_{max} to three different loops. If "NO" occurs in the criteria $f_{min} \leq f_n \leq f_{max}$, a second parameter cutting speed V will be optimised. The logic of optimising V is the same as with the left section, as Figure 5-17 shows.

Step five: if 1.05Fd<F<=1.1Fd, F_{max} goes to the second loop where △f=1/2△f. and the logic is similar to that of the first loop. The formula of the golden ratio and the number of criteria is different from the first loop.

Step six: if 1.02Fd<F<=1.05Fd, F_{max} goes to the second loop where △f=1/50△f. The reason △f=1/50△f is because F_{max} is very close to Fd, therefore, if △f is too big (for example, as ¼ or 1/8 △f), step over might occur and the optimum will not be reached. Although a smaller △f will lead to a longer calculation time, tests shows the setup has little influence to the calculation time.

Step seven: if 0.98Fd<=F<=1.02Fd, the system will output the current feed rate, because F meets the expectation of the system.

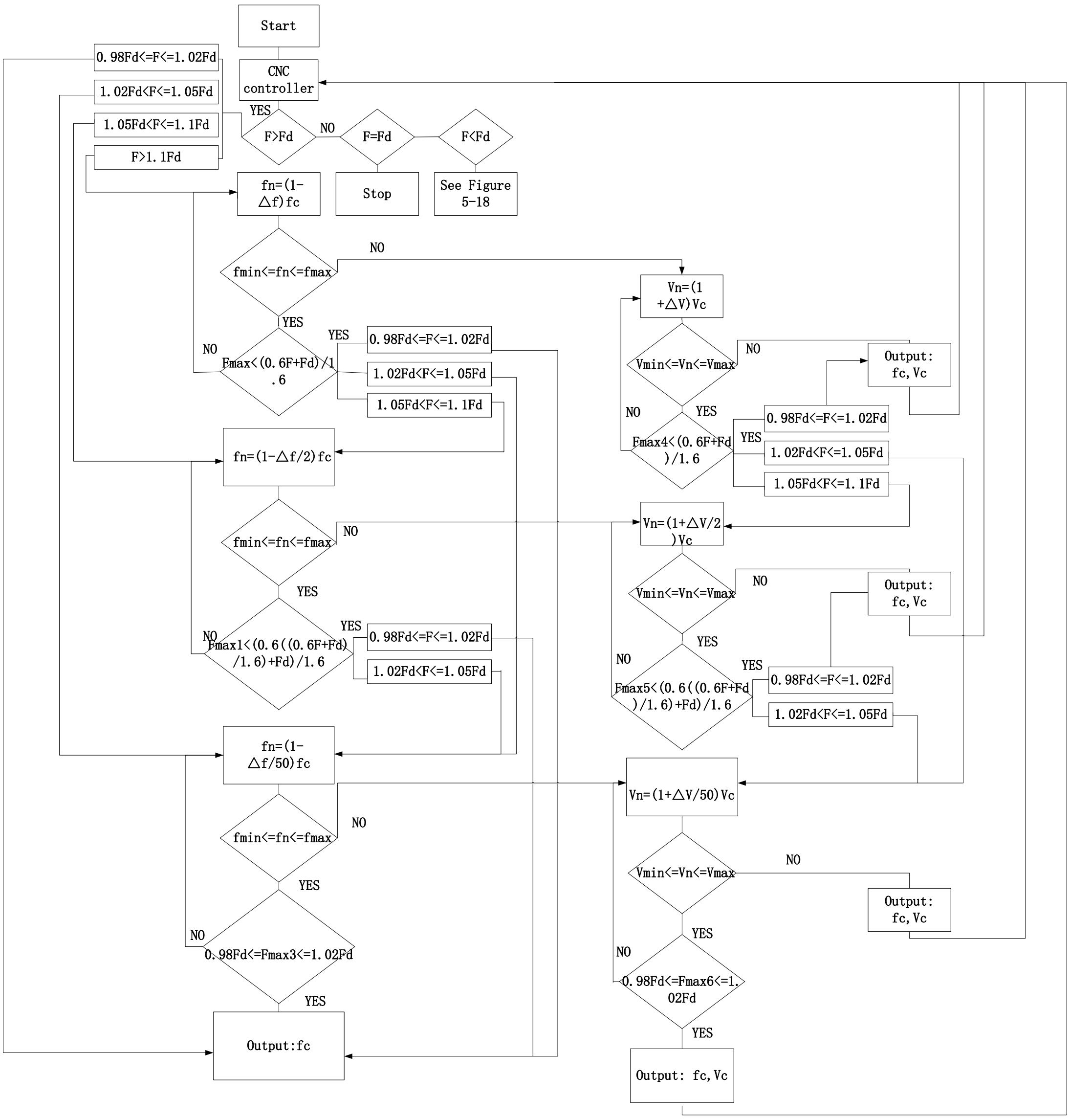

Figure 5-17 Final model when measured cutting force is bigger than reference value

Figure 5-18 shows the logic when F<Fd, and the logic is similar to the Figure 5-17; detailed explanations are similar to the seventh step above. The main differences are the formula of golden ratios and the value of criteria.

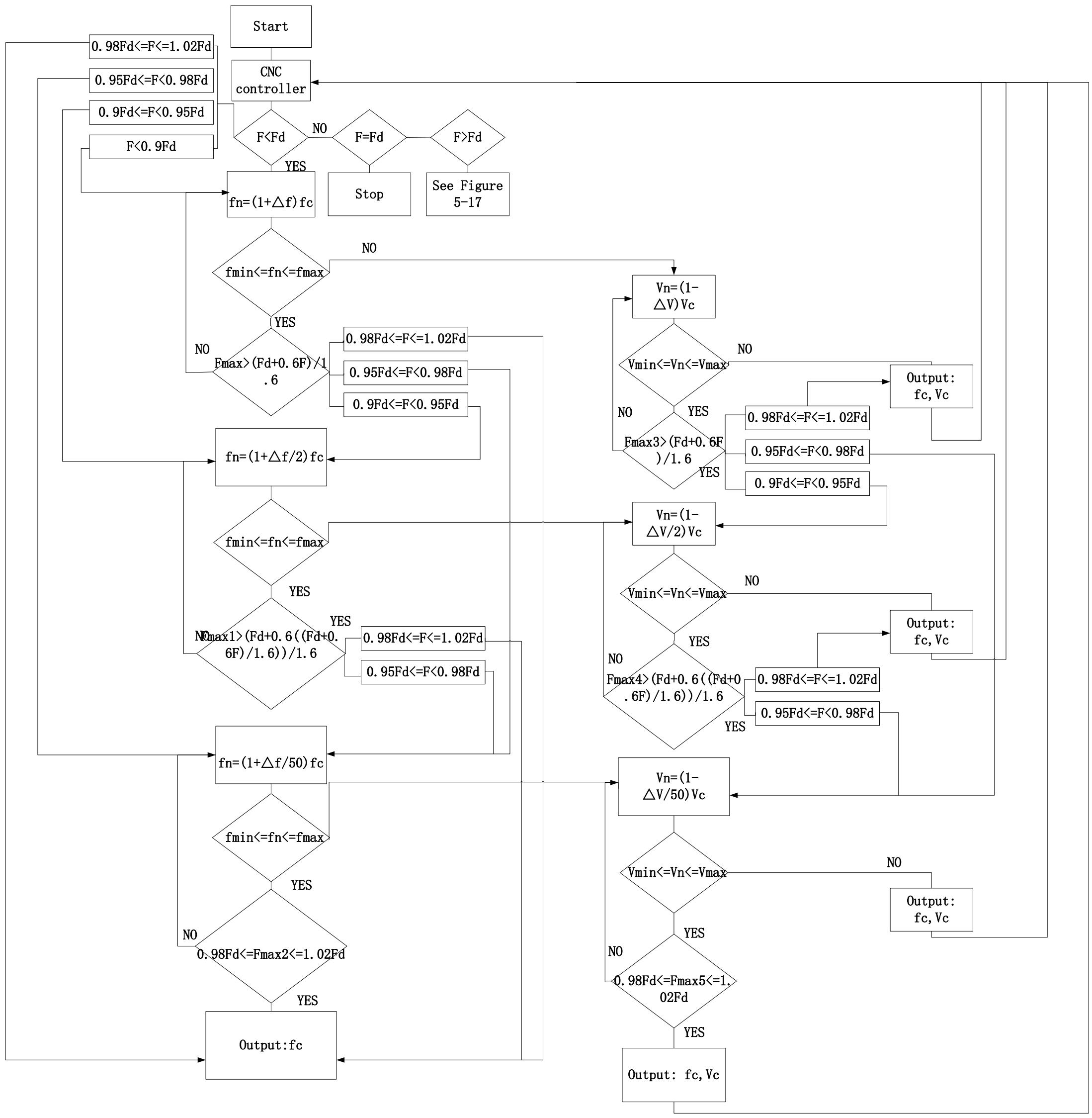

Figure 5-18 Final model when measured cutting force is smaller than reference value

The optimisation method of the system is based on the Hill Climbing (HC) method, however the final system is different to conventional HC. An adaptive step as △f is applied to reduce the calculation time and a different setup of △f will prevent the step over. The input F is located by four criteria; this design increases the speed of the system, making F approach Fd quicker and in the meantime, preventing the step over. Finally, the optimum is designed in a zone of ±2% of Fd, because the expectation of how stable the cutting force is different individually. Some companies might regard ±5% as sufficient, whereas some might think this of ±1%. The companies can set the value according to their own standards.

6 Validation

6.1 Case study

The case study is based on a real case, and the cutting force and set of parameters are based on Adolfsson et al, (1995). The geometry of the raw material is shown in Fig.6-1. The material of the workpiece is SS2172, a steel combined with 0.20% C, 0.30% Si, 1.3% Mn, 0.05% P, 0.05% S, 0.3% Cr, 0.4% Cu, and 0.01% N (Adolfsson et al,. 1995). The geometry of the raw material is used to machine an iPphone case. It is small and light, which in this study is the reason that the acceleration and deceleration time of the feed rate is ideally regarded as zero. A 18KW milling centre produced by SAJO is chosen as the most appropriate machine to carry out the experiments. The maximum spindle speed of the machine is 7500 rpm.

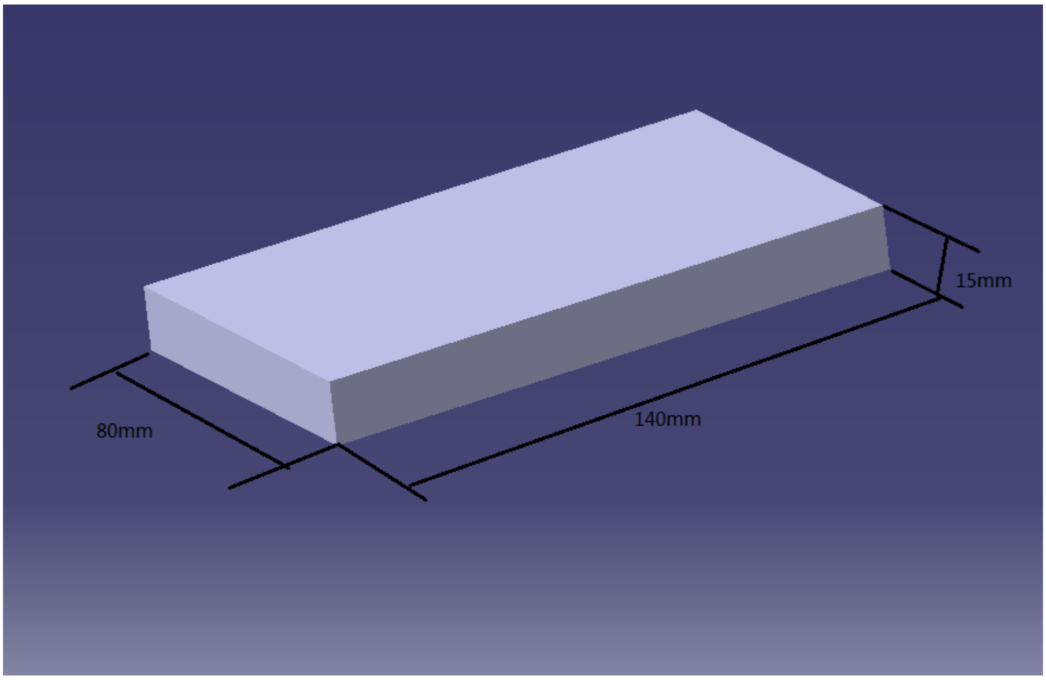

Figure 6-1 The geometry of the raw material

A detailed set of parameters is shown in Table 6-1, where a 125mm cutter with 8 cutting edges is used to carry out the experiments. Based on the set of parameters, during the machining process, four cutting edges will work simultaneously as Figure 6-2 shows.

Table 6-1 Parameters for the experiment

Cutting resistance C_r	1750(N/mm^2)
Tool diameter D	125(mm)
Number of cutting edge z	8
Width of chip b	1.5(mm)
Width of cut d	110(mm)
Cutting speed V	120 (m/min)
Reference cutting force Fd	1000(N)
Start feed rate F	0.6(m/min)
Start feed per tooth f	0.125(mm/tooth)

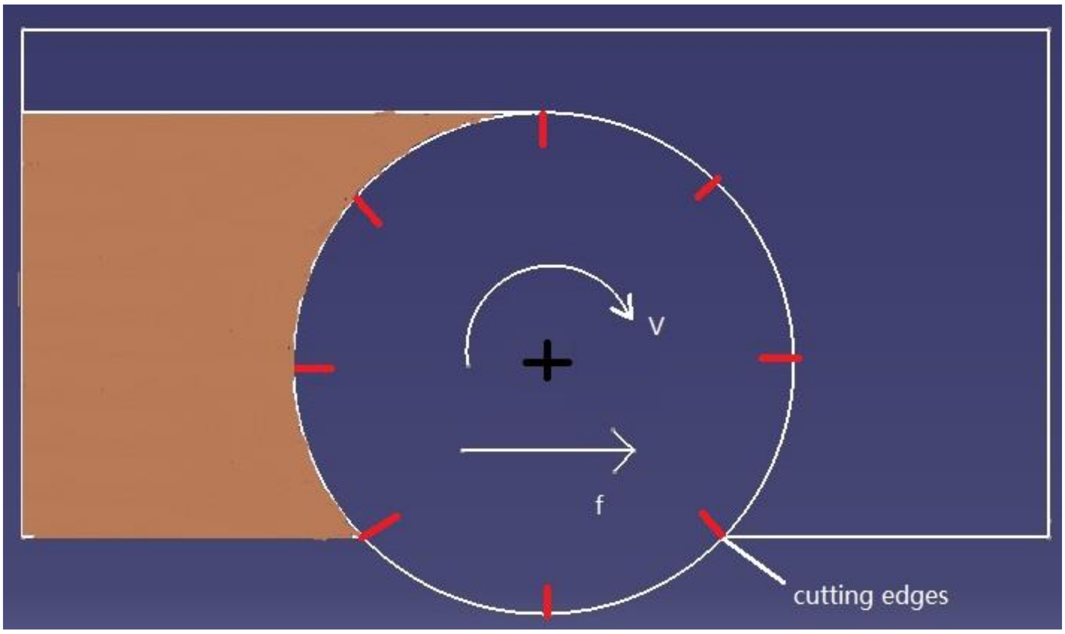

Figure 6-2 Four cutting edges work simultaneously

As previously mentioned, four cutting edges work at the same time during the machining process, and each cutting force of the cutting edges are measured as shown in Figure 6-3, Figure 6-4, Figure 6-5, Figure 6-6. Based on the measurements, each cutting edge needs 0.05sec to finish cutting, and every 0.0125 sec, a new cutting edge will come into the cutting area, which means a cutting cycle for four cutting edges to finish cutting will need 0.0875 sec, adding some delay caused by the measurement, This cycle time is regarded as 0.1sec.

From the four Figures below, it is easy to deduce that during each cutting cycle, the cutting condition is similar. For each cutting edge, when the cutting edge comes into the cutting area, the cutting force will initially have a sharp increase until it reaches a certain value. For cutting edge one, the maximum cutting force is around 350N, the cutting force will stay around the maximum value until it finishes the cutting and the cutting force will drop to zero immediately.

Clearly, the cutting forces of cutting edges one and two are bigger than for cutting edge three and four. The reason this happens is because when cutting edge one and two are still in the cutting area, the material had been removed when cutting edges three or four come into the area, however, these two cutting edges only cut a very thin layer of material.

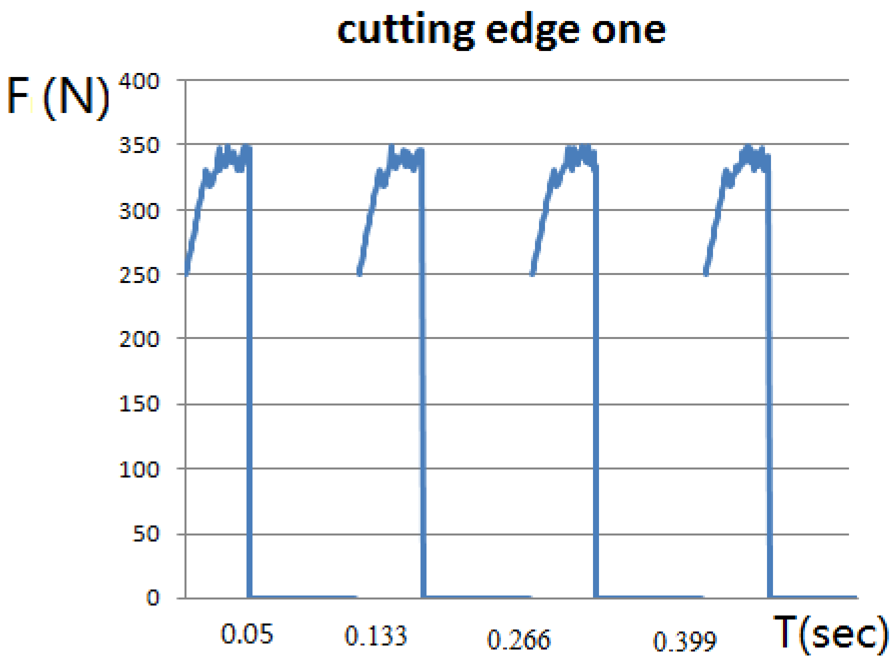

Figure 6-3 Cutting force for cutting edge one

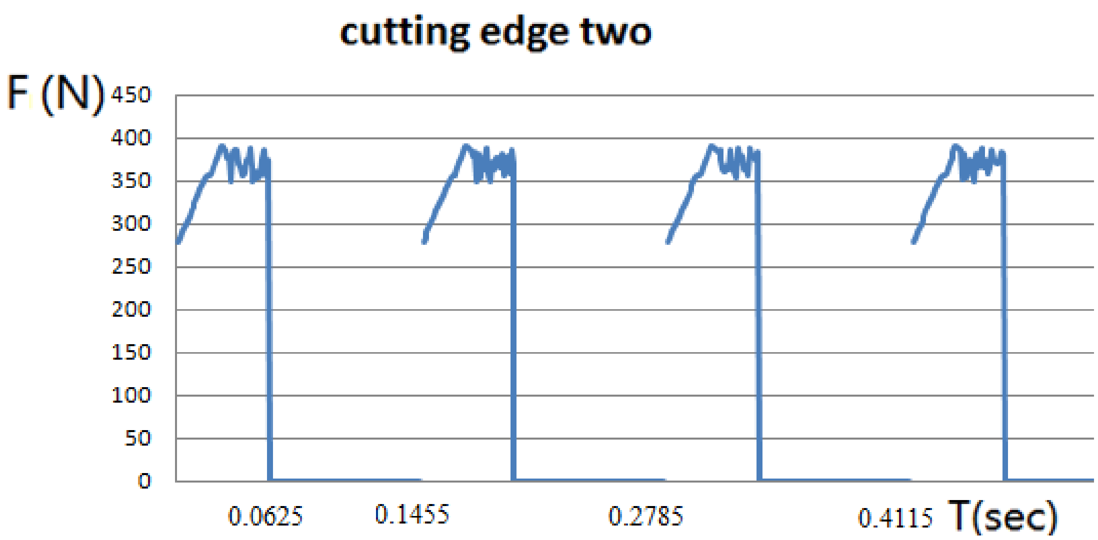

Figure 6-4 Cutting force for cutting edge two

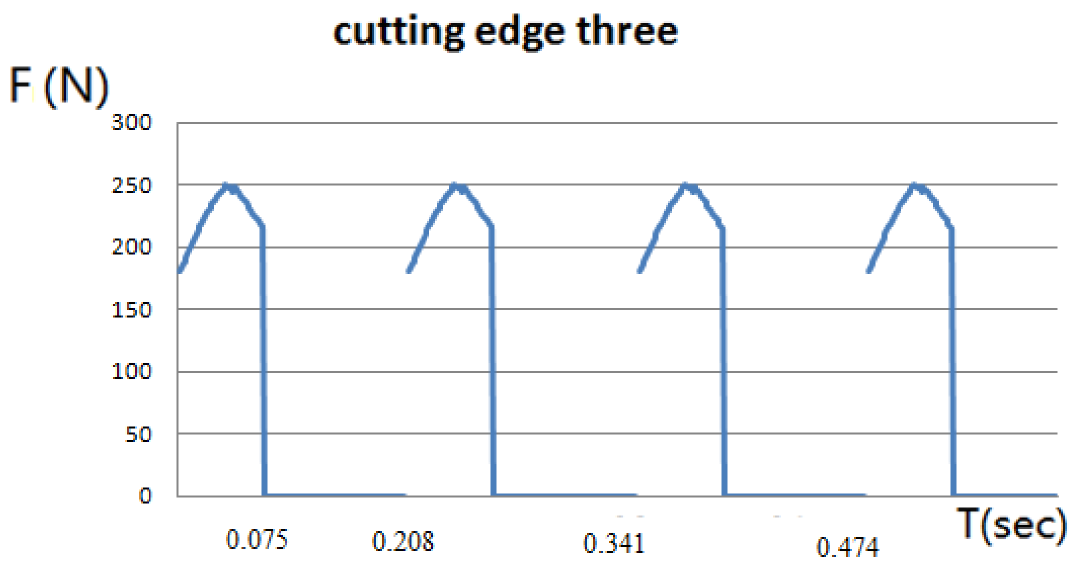

Figure 6-5 Cutting force for cutting edge three

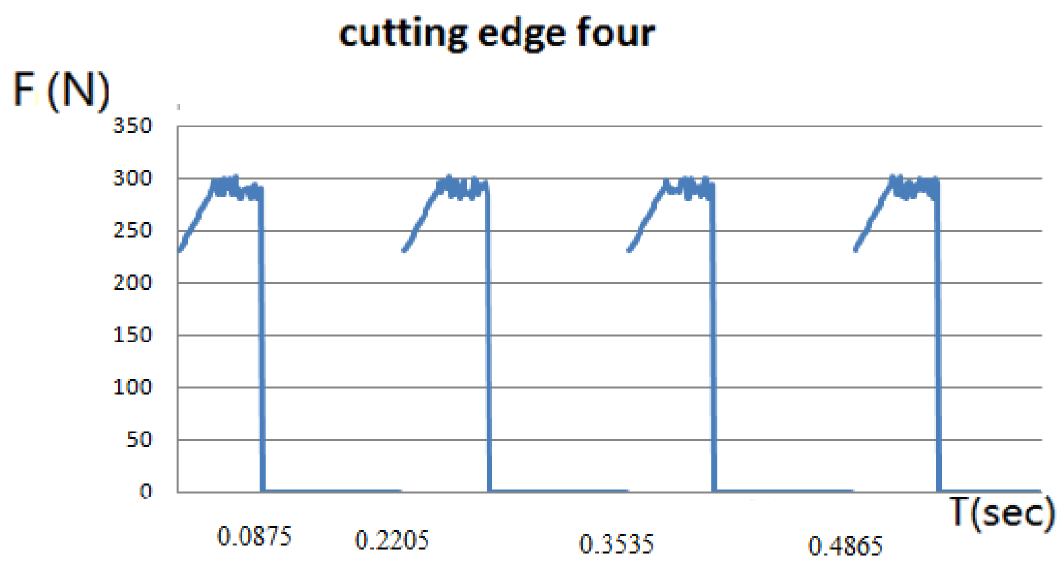

Figure 6-6 Cutting force for cutting edge four

The total cutting force is the sum of the four cutting forces of the cutting edges, as mentioned above. The cutting cycle for four cutting edges to finish cutting is 0.1sec, and the total cutting force count is 5 cutting cycles as Figure 6-8 shows. The maximum cutting force is approximately 1300 N, and the reference Fd is set at 1000 N. Clearly, the cutting force is larger than the reference value most of the time, which is also normal in real life.

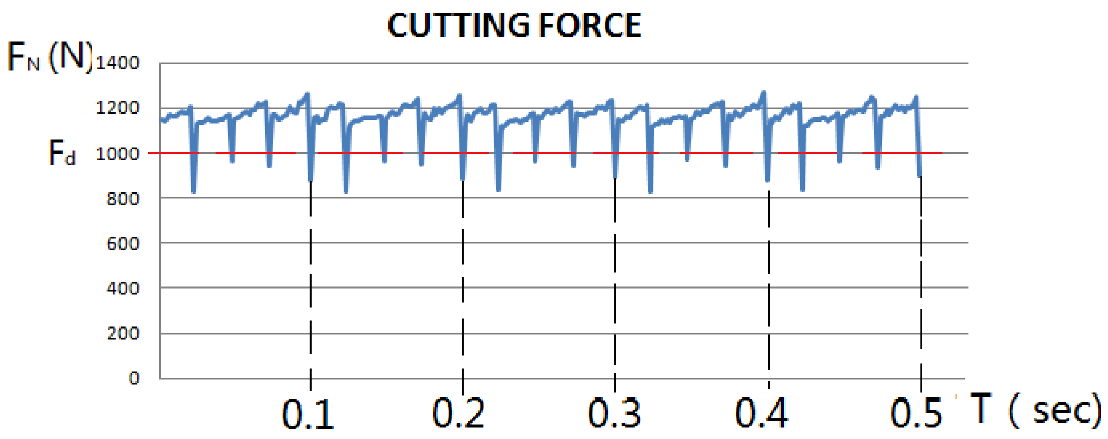

Figure 6-7 Total cutting fore before optimisation

The optimisation programme will run once every 120ms based on the ideal situation that the reaction of the CNC controller and the CNC machine needs no time. Figure 6-8 shows the cutting force after the optimisation. It is easy to deduce that the first cycle has not been optimised because after the first signal was obtained, 120 ms was needed to carry out the action. The first signal obtained is larger than the reference value, and based on the logic presented in Chapter 5, the feed rate should be reduced to decrease the cutting force. The cutting force starts to reduce gradually at point A. At point B, the cutting force reaches the optimum value. The reason the cutting force needs a process to decrease is because the CNC machine needs time to decelerate feed rate. From point B to C, the cutting force is stabilised for a short time until the end of the cutting cycle. When a new cutting cycle begins, the cutting force increases sharply to the maximum point D. The next optimisation cycle occurs 120 ms after the first signal was obtained.

The running time of the programme is short, and will depend on the speed of CUP. However, during each calculation, the programme will average all 10 times of the objective function, which is extremely fast. The running time for a normal laptop is 20 ms, but for a new CPU of CNC controller it will take less time. This is another reason that the ideal running time is regarded as zero in this study.

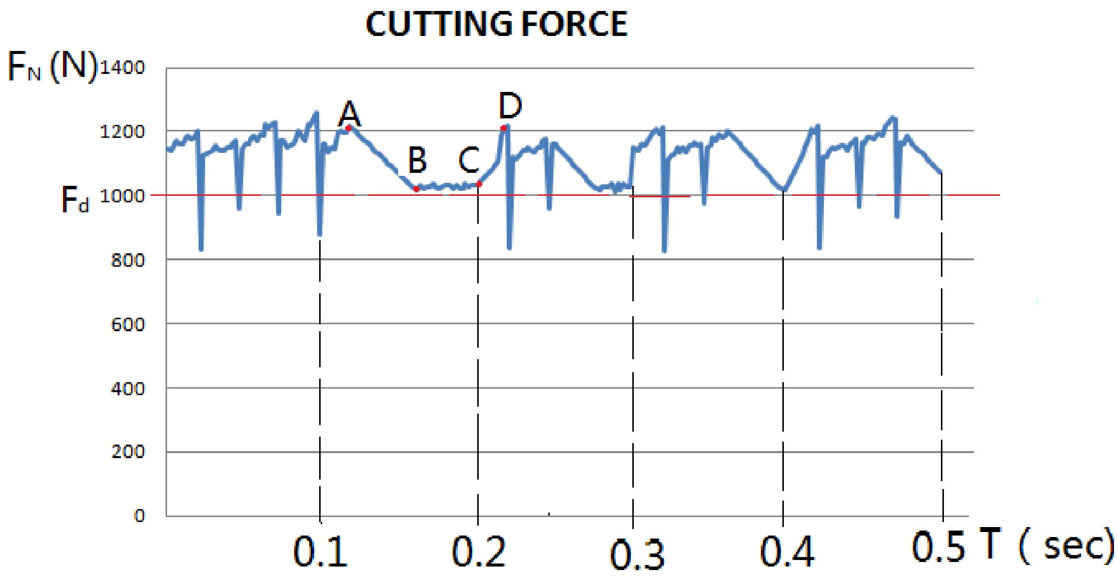

Figure 6-8 Total cutting force after optimisation

The feed rate of the cutting process is decreased as the cutting force reduced which might increase cutting time. According to some researchers, this occurs sometimes; feed rate decreases to maintain a more stable cutting process. Figure 6-9 shows the change of feed rate. It is obvious that when the cutting force starts to reduce, the feed rate starts to decrease, as the blue line shows in Fig.6-9. The feed rate reaches the minimum when the cutting force reaches the optimum value. Following this, the feed rate stays stable for a short time until the end of the cutting cycle.

In this paper, the cutting process is face milling with a simple one way cut, and the cutting force and feed rate are not as dramatic as the complex milling process. The cutting force in this paper is essentially beyond the reference value, and feed rate is the only parameter to adjust. However, in a normal face milling process with a complex workpiece, the cutting force is more complex than in this paper, therefore, several different values of feed rate need to be set to deal with corner, pocket and slot. Different situations, as presented in Chapter 5, are possible, therefore, feed rate and cutting speed can be optimised in one milling process.

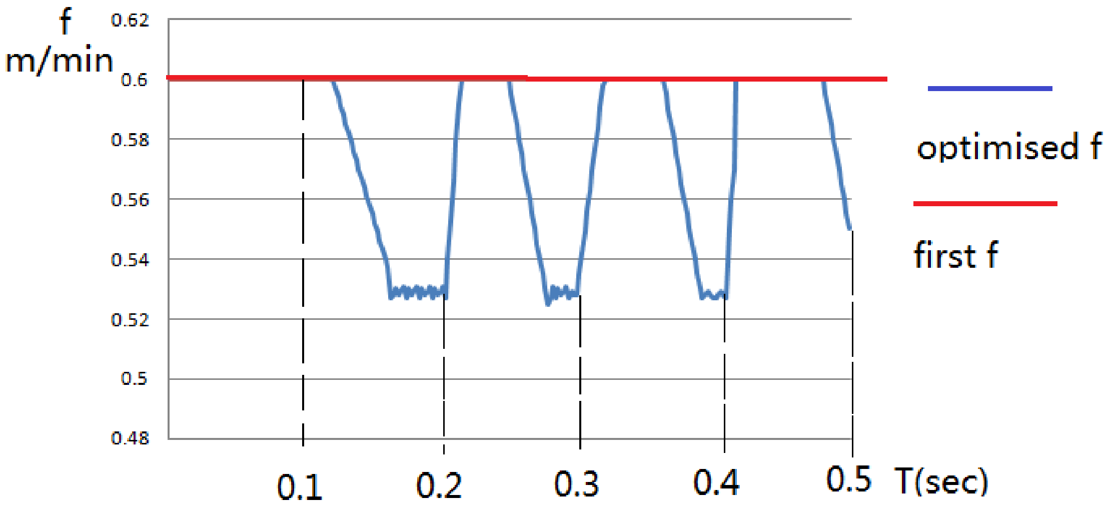

Figure 6-9 Feed rate change according to the change of cutting force

7 Conclusion and discussion

7.1 Conclusion

This study presents a Function Block based real-time optimisation model. The cutting force model is used to carry out the optimisation. Based on the cutting force function of a single cutting edge, the research developed a series of objective functions to calculate the total cutting force according to a different number of cutting edges and cutting situations. The objective function presented is less accurate than the calculation of a complex model, but it is faster with acceptable errors. Another benefit of the simplified objective function is that by using these functions, the running time of the programme is much shorter.

The model presented is proven to be capable of stabilising the cutting force with the calculation time within 10 ms if using an advanced CPU. The feed rate is decreased compared to the initial rate, however the cutting process is more stable. Furthermore, the model provides the possibility to carry out automated control and optimisation. When something unexpected happens such as an extremely high cutting force, the model can deal with the situation within 120 ms without a human operator.

However, unexpected cutting force overload is one of the most common uncertainties in the milling process. Future work will focus on combining other uncertainties in the model such as tool vibration, tool heat, workpiece vibration, workpiece heat, load on the axes, sounds and power consumption. By simplifying the objective functions similar to this paper, the mode might have the ability to deal with multiple uncertainties with fast reactions.

7.2 Discussion

This research is an early attempt to apply a Function Block based Cloud system in real-time optimisation. Currently, this kind of system still needs in depth development. More research is needed to prove the system is valuable in order to attract more researchers and companies. The two major problems of FB based Cloud systems are: FBs are not supported by most of the CNC machines, therefore the machines cannot run FB directly; and FB code needs to be translated into G-code in order to run in the CNC machines, thus, special FBs that can translate FB code into G-code need to be developed.

Simulation validation can reflect the result that, to some extent, real-life experiments are the most reliable way of validation. Especially in machining processes, simulation usually builds up an ideal environment in which most of the variables are regarded as constant. The result of simulation can reflect the tendency of the expectation.

Only cutting force signal and one FB is used in the research, according to the tendency of the development of CNC machines. More signals can be used in the FB based Cloud system such as tool vibration, tool heat, workpiece vibration, workpiece heat, load on the axes, sounds and power consumption. A more complex system can be built, where multiple FBs are used to build a relationship between running parameters and above signals which can deal with all kinds of uncertainties in the machining process. This kind of system has the ability to self-control and optimise in any situation in real-time and, thus, high intelligence and automation of the CNC machine can be achieved as Figure 7-1 shows. The CNC controller will transfer multiple signals such as force signal, vibration signal, heat signal, sound signal, power signal and sound signal to the Function Blocks. The Function Blocks are capable of dealing with the input signals based on the inside algorithms. Multiple parameters can be optimised and then fed back to the CNC controller.

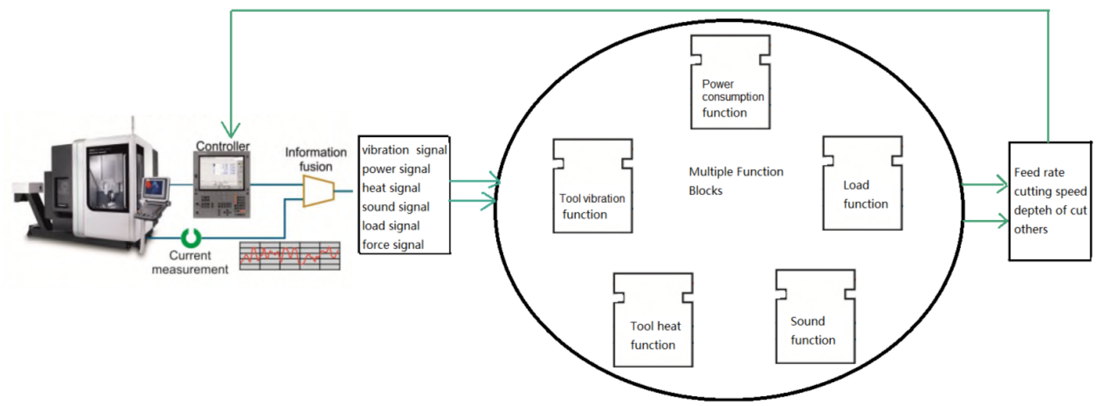

Figure 7-1 multiple Function Blocks based system

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Zhu, L., Zheng, G., Ding, H., & Xiong, Y. (2010). Global optimisation of tool path for five-axis flank milling with a conical cutter. Computer-Aided Design, 42(10), 903-910.

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APPENDICES

APPENDIX A List of off-line optimisation

Writer	Optimised factors	Objective	Methods	reference	link
Ali R. Yildiz, 2013	Optimise feed	Maximum production rate	novel hybrid optimisation approach based on differential evolution algorithm and receptor editing property of immune system	Yildiz, A. R. (2013). A new hybrid differential evolution algorithm for the selection of optimal machining parameters in milling operations. Applied Soft Computing, 13(3), 1561-1566.	http://www.sciencedirect.com/science/article/pii/S156849461100500X
Azlan Mohd Zaina et al., 2010	Optimise the combination of cutting speed, feed, radial rake angle	Minimum surface roughness	genetic algorithm	Zain, A. M., Haron, H., & Sharif, S. (2010). Application of GA to optimise cutting conditions for minimizing surface roughness in end milling machining process. Expert Systems with Applications, 37(6), 4650-4659.	http://www.sciencedirect.com/science/article/pii/S0957417409010896
C.N. Chu et al., 1997	Optimise feed	Reduce production time	a novel method	Chu, C. N., Kim, S. Y., Lee, J. M., & Kim, B. H. (1997). Feed-rate optimisation of ball end milling considering local shape features. CIRP Annals-Manufacturing Technology, 46(1), 433-436.	http://www.sciencedirect.com/science/article/pii/S0007850607608592
Clodeinir Ronei Peres et al., 1999	Optimise feed, and MRR	Stabilize cutting force	fuzzy logic	Peres, C. R., Guerra, R. E. H., Haber, R. H., Alique, A., & Ros, S. (1999). Fuzzy model and hierarchical fuzzy control integration: an approach for milling process optimisation. Computers in Industry, 39(3), 199-207.	http://www.sciencedirect.com/science/article/pii/S0166361598001365
Dae Kyun Bae et al., 2001	Optimise feed	Minimum surface roughness	a novel method	Baek, D. K., Ko, T. J., & Kim, H. S. (2001). Optimisation of feedrate in a face milling operation using a surface roughness model. International Journal of Machine Tools and Manufacture, 41(3), 451-462.	http://www.sciencedirect.com/science/article/pii/S0890695500000390
E. J. A. Armarego et al., 1994	Optimise feed and cutting speed	Minimum production time	constrained optimisation	Armarego, E. J. A., Smith, A. J. R., & Wang, J. (1994). Computer-aided constrained optimisation analyses and strategies for multipass helical tooth milling operations. CIRP Annals-Manufacturing Technology, 43(1), 437-442.	http://www.sciencedirect.com/science/article/pii/S0007850607622483

Ganping Sun et al., 2005	Optimise feed, cutting speed , width of cut	Minimum production time	a novel method	Sun, G., & Wright, P. (2005). Simulation-based cutting parameter selection for ball end milling. Journal of manufacturing systems, 24(4), 352-365.	http://www.sciencedirect.com/science/article/pii/S0278612505800196
Gianni Campatelli et al.,2014	Optimise feed, cutting speed, depth of cut	Minimum the power consumption	Response Surface Method	Campatelli, G., Lorenzini, L., & Scippa, A. (2014). Optimisation of process parameters using a Response Surface Method for minimizing power consumption in the milling of carbon steel. Journal of Cleaner Production, 66, 309-316.	http://www.sciencedirect.com/science/article/pii/S095965261300704X
Godfrey C et al., 2006	Optimise feed, depth of cut , cuttiing speed	Maximum production rate	Tribes	Onwubolu, G. C. (2006). Performance-based optimisation of multi-pass face milling operations using Tribes. International Journal of Machine Tools and Manufacture, 46(7), 717-727.	http://www.sciencedirect.com/science/article/pii/S0890695505001926
H. El-Mounayr et al., 2005	Optimisefeed, depth of cut spindle speed	Minimum production time	artificial neural networks (ANN)	El-Mounayri, H., Kishawy, H., & Briceno, J. (2005). Optimisation of CNC ball end milling: a neural network-based model. Journal of Materials Processing Technology, 166(1), 50-62.	http://www.sciencedirect.com/science/article/pii/S0924013604009951
H. Pereza et al., 2013	Optimise cutting parameters	Reduce tool wear	a novel method	Perez, H., Diez, E., Perez, J., & Vizan, A. (2013). Analysis of machining strategies for peripheral milling. Procedia Engineering, 63, 573-581.	http://www.sciencedirect.com/science/article/pii/S1877705813014069
Hsin-Ta Hsieh et al., 2013	Optimise tool path	Reduce machine error	AdvancedParticleSwarmOptimisation (APSO)andFullyInformedParticleSwarmOptimisation(FIPS)algorithms	Hsieh, H. T., & Chu, C. H. (2013). Improving optimisation of tool path planning in 5-axis flank milling using advanced PSO algorithms. Robotics and Computer-Integrated Manufacturing, 29(3), 3-11.	http://www.sciencedirect.com/science/article/pii/S0736584512000531
J.A. Ghani et al., 2004	Optimise feed, cutting speed, depth of cut	Minimum surface roughness	Taguchi optimisation	Ghani, J. A., Choudhury, I. A., & Hassan, H. H. (2004). Application of Taguchi method in the optimisation of end milling parameters. Journal of Materials Processing Technology, 145(1), 84-92.	http://www.sciencedirect.com/science/article/pii/S0924013603008653
Jenq-Shyong By Chen et al.,2005	Optimise feed	Minimum production time	a novel method	Chen, J. S., Huang, Y. K., & Chen, M. S. (2005). Feedrate optimisation and tool profile modification for the high-	http://www.sciencedirect.com/science/article/pii/S0890695504003062

				efficiency ball-end milling process. International Journal of Machine Tools and Manufacture, 45(9), 1070-1076.	
Jihong Yan et al., 2013	Optimise MRR	Minimum surface roughness Minimum the power consumption	weighted grey relational analysis and response surface methodology (RSM)	Yan, J., & Li, L. (2013). Multi-objective optimisation of milling parameters–the trade-offs between energy, production rate and cutting quality. Journal of Cleaner Production, 52, 462-471.	http://www.sciencedirect.com/science/article/pii/S0959652613001017
Kaan Erkorkmaz et al., 2013	Optimise feed	Minimum cycle time tool trajectories	a novel method	Erkorkmaz, K., Layegh, S. E., Lazoglu, I., & Erdim, H. (2013). Feedrate optimisation for freeform milling considering constraints from the feed drive system and process mechanics. CIRP Annals-Manufacturing Technology, 62(1), 395-398.	http://www.sciencedirect.com/science/article/pii/S0007850613000851
Liang Gao et al.,2012	Optimise feed and cutting speed	MinImun production time	cellular particle swarm optimisation	Gao, L., Huang, J., & Li, X. (2012). An effective cellular particle swarm optimisation for parameters optimisation of a multi-pass milling process. Applied Soft Computing, 12(11), 3490-3499.	http://www.sciencedirect.com/science/article/pii/S1568494612002785
LiMin Zhu et al.,2010	Optimise tool path	Increase machining accuracy	a sequential approximation algorithm along with a hierarchical algorithmic structure	Zhu, L., Zheng, G., Ding, H., & Xiong, Y. (2010). Global optimisation of tool path for five-axis flank milling with a conical cutter. Computer-Aided Design, 42(10), 903-910.	http://www.sciencedirect.com/science/article/pii/S001044851000120X
Lohithaksha M Maiyara et al.,2013	Optimise feed, cutting speed, depth of cut	MinImun production time Minimum production cost	taguchi orthogonal array with the grey relational analysis	Maiyar, L. M., Ramanujam, R., Venkatesan, K., & Jerald, J. (2013). Optimisation of Machining Parameters for end Milling of Inconel 718 Super Alloy Using Taguchi based Grey Relational Analysis. Procedia Engineering, 64, 1276-1282.	http://www.sciencedirect.com/science/article/pii/S1877705813017220
Luis Rubio et al., 2013	Optimise MRR	Minimum production cost	expert rule-based system	Rubio, L., De la Sen, M., Longstaff, A. P., & Fletcher, S. (2013). Model-based expert system to automatically adapt milling forces in Pareto optimal multi-objective working points. Expert Systems with Applications, 40(6), 2312-2322.	http://www.sciencedirect.com/science/article/pii/S095741741201158X
M. TOLOUEI-RAD et al., 1996	Optimise feed, cutting speed	Minimum production cost	constraint-based optimisation	Tolouei-Rad, M., & Bidhendi, I. M. (1997). On the optimisation of machining parameters for milling	http://www.sciencedirect.com/science/article/pii/S0890695596000442

		Maximum production rate		operations. International Journal of Machine Tools and Manufacture, 37(1), 1-16.	
M.S. Shunmugam et al., 2000	Optimise feed, depth of cut spindle speed, number of passed	Minimum production cost	genetic algorithm	Shunmugam, M. S., Bhaskara Reddy, S. V., & Narendran, T. T. (2000). Selection of optimal conditions in multi-pass face-milling using a genetic algorithm. International Journal of Machine Tools and Manufacture, 40(3), 401-414.	http://www.sciencedirect.com/science/article/pii/S0890695599000632
M.Subramania et al., 2013	Optimise feed, cutting speed, depth of cut	Stabilize cutting force	genetic algorithms	Subramanian, M., Sakthivel, M., Sooryaprakash, K., & Sudhakaran, R. (2013). Optimisation of Cutting Parameters for Cutting Force in Shoulder Milling of Al7075-T6 Using Response Surface Methodology and Genetic Algorithm. Procedia Engineering, 64, 690-700.	http://www.sciencedirect.com/science/article/pii/S1877705813016585
Mohamad Syahmi Shahrom et al., 2013	Optimise lubrication	Minimum surface roughness	Taguchi Method	Shahrom, M. S., Yahya, N. M., & Yusoff, A. R. (2013). Taguchi Method Approach on Effect of Lubrication Condition on Surface Roughness in Milling Operation. Procedia Engineering, 53, 594-599.	http://www.sciencedirect.com/science/article/pii/S1877705813001951
O. Zareia et al., 2009	Optimise feed, depth of cut spindle speed, number of passed	Minimum production cost	harmony search (HS) algorithm	Zarei, O., Fesanghary, M., Farshi, B., Saffar, R. J., & Razfar, M. R. (2009). Optimisation of multi-pass face-milling via harmony search algorithm. Journal of materials processing technology, 209(5), 2386-2392.	http://www.sciencedirect.com/science/article/pii/S0924013608004470
Qinghua Song et al.,2014	Optimise MRR and spindle speed	Reduce vibration	a novel method	Song, Q., Ju, G., Liu, Z., & Ai, X. (2014). Subdivision of chatter-free regions and optimal cutting parameters based on vibration frequencies for peripheral milling process. International Journal of Mechanical Sciences, 83, 172-183.	http://www.sciencedirect.com/science/article/pii/S0020740314001258
R. Salami et al., 2007	Optimise feed	MinImun production time Reduce tool wear	a novel method	Salami, R., Sadeghi, M. H., & Motakef, B. (2007). Feed rate optimisation for 3-axis ball-end milling of sculptured surfaces. International Journal of Machine Tools and Manufacture, 47(5), 760-767.	http://www.sciencedirect.com/science/article/pii/S0890695506002306
R. Venkata Rao et al., 2010	Optimise feed, depth of cut cuttiing speed	MinImun production time	artificial bee colony (ABC), particle swarm optimisation (PSO), and simulated annealing (SA).	Venkata Rao, R., & Pawar, P. J. (2010). Parameter optimisation of a multi-pass milling process using non-traditional optimisation algorithms. Applied soft computing, 10(2), 445-456.	http://www.sciencedirect.com/science/article/pii/S156849460900132X

S. Doruk Merdol et al., 2008	Optimise MRR	MinImun production time	constraint-based optimisation	Merdol, S. D., & Altintas, Y. (2008). Virtual cutting and optimisation of three-axis milling processes. International Journal of Machine Tools and Manufacture, 48(10), 1063-1071.	http://www.sciencedirect.com/science/article/pii/S0890695508000461
S. Ehsan Layegh K. et al., 2012	Optimise feed	Stabilize cutting force	a novel method	Layegh, K. S. E., Erdim, H., & Lazoglu, I. (2012). Offline force control and feedrate scheduling for complex free form surfaces in 5-axis milling. Procedia CIRP, 1, 96-101.	http://www.sciencedirect.com/science/article/pii/S2212827112000169
Sonmez, A.I. et al., 1999	Optimise feed and cutting speed	MinImun production time	geometric programmin	Sönmez, A. I., Baykasoğlu, A., Dereli, T., & Fılız, I. H. (1999). Dynamic optimisation of multipass milling operations via geometric programming. International Journal of Machine Tools and Manufacture, 39(2), 297-320.	http://www.sciencedirect.com/science/article/pii/S0890695598000273
T.G. Brito et al.,2014	Optimise cutting parameters	Minimum surface roughness	normal boundary intersection (NBI) method coupled with mean-squared error (MSE)	Brito, T. G., Paiva, A. P., Ferreira, J. R., Gomes, J. H. F., & Balestrassi, P. P. (2014). A normal boundary intersection approach to multiresponse robust optimisation of the surface roughness in end milling process with combined arrays. Precision Engineering, 38(3), 628-638.	http://www.sciencedirect.com/science/article/pii/S0141635914000439
Turgay Kıvak, 2014	Optimise feed, cutting speed	Minimum surface roughness Reduce tool wear	Taguchi method and regression analysis	Kıvak, T. (2014). Optimisation of surface roughness and flank wear using the Taguchi method in milling of Hadfield steel with PVD and CVD coated inserts. Measurement, 50, 19-28.	http://www.sciencedirect.com/science/article/pii/S0263224113006386
V. Tandon et al., 2002	Optimise feed and cutting speed	MinImun production cost	particle swarm optimisation (PSO) artificial neural networks (ANN)	Tandon, V., El-Mounayri, H., & Kishawy, H. (2002). NC end milling optimisation using evolutionary computation. International Journal of Machine Tools and Manufacture, 42(5), 595-605.	http://www.sciencedirect.com/science/article/pii/S0890695501001511
Xiaoming Zhang et al.,2013	Optimise MRR	Minimum tool vibration	augmented Lagrangian function method	Zhang, X., & Ding, H. (2013). Note on a novel method for machining parameters optimisation in a chatter-free milling process. International Journal of Machine Tools and Manufacture, 72, 11-15.	http://www.sciencedirect.com/science/article/pii/S0890695513000655

Xiaoming Zhang et al.,2012	Optimise spindle speed	Stabilize cutting process	augmented Lagrangian function method	Zhang, X., Zhu, L., Zhang, D., Ding, H., & Xiong, Y. (2012). Numerical robust optimisation of spindle speed for milling process with uncertainties. International Journal of Machine Tools and Manufacture, 61, 9-19.	http://www.sciencedirect.com/science/article/pii/S0890695512000788
Yong-Gang Kangn et al., 2013	Optimise depth of cut	Stabilize cutting force Reduce tool vibration	flexible iterative algorithm (FIAL)	Kang, Y. G., & Wang, Z. Q. (2013). Two efficient iterative algorithms for error prediction in peripheral milling of thin-walled workpieces considering the in-cutting chip. International Journal of Machine Tools and Manufacture, 73, 55-61.	http://www.sciencedirect.com/science/article/pii/S0890695513000916
Z.G. Wang et al., 2005	Optimise feed, spindle speed，depth of cut	Stabilize cutting process	parallel genetic simulated annealing (PGSA)	Wang, Z. G., Rahman, M., Wong, Y. S., & Sun, J. (2005). Optimisation of multi-pass milling using parallel genetic algorithm and parallel genetic simulated annealing. International Journal of Machine Tools and Manufacture, 45(15), 1726-1734.	http://www.sciencedirect.com/science/article/pii/S0890695505000775

APPENDIX B List of on-line optimisation

Writer	Optimised factors	Objectives	methods	reference	
F. Cus et al., 2006	Optimise feed, cutting speed, depth of cut	Stabilize cutting force Reduce production time	genetic algorithms	Cus, F., Milfelner, M., & Balic, J. (2006). An intelligent system for monitoring and optimisation of ball-end milling process. Journal of Materials Processing Technology, 175(1), 90-97.	http://www.sciencedirect.com/science/article/pii/S0924013605004462
M. Milfelner et al., 2005	Optimise feed, cutting speed, depth of cut	Increase machining efficiency	genetic algorithms	Milfelner, M., Cus, F., & Balic, J. (2005). An overview of data acquisition system for cutting force measuring and optimisation in milling. Journal of materials processing technology, 164, 1281-1288.	http://www.sciencedirect.com/science/article/pii/S0924013605001184
P. Bosettia et al., 2013	Optimise feed, spindle speed	Stabilize machining process Increase machining efficiency	a novel method	Bosetti, P., Leonesio, M., & Parenti, P. (2013). On Development of an Optimal Control System for Real-time Process Optimisation on Milling Machine Tools. Procedia CIRP, 12, 31-36.	http://www.sciencedirect.com/science/article/pii/S2212827113006483
Shiuh-Tarng Chiang et al., 1995	Optimise feed	Increase machining efficiency	artificial neural networks (ANN)	Chiang, S. T., Liu, D. I., Lee, A. C., & Chieng, W. H. (1995). Adaptive control optimisation in end milling using neural networks. International Journal of Machine Tools and Manufacture, 35(4), 637-660.	http://www.sciencedirect.com/science/article/pii/0890695594P4355X
U. Zuperl et al., 2005	Optimise feed	Reduce tool wear Reduce production time	fuzzy logic	Zuperl, U., Cus, F., & Milfelner, M. (2005). Fuzzy control strategy for an adaptive force control in end-milling. Journal of Materials Processing Technology, 164, 1472-1478.	http://www.sciencedirect.com/science/article/pii/S0924013605001445
Luis Rubio et al., 2013	Optimise feed, cutting speed, depth of cut	Reduce production cost Increase machining efficiency	expert rule-based system	Rubio, L., De la Sen, M., Longstaff, A. P., & Fletcher, S. (2013). Model-based expert system to automatically adapt milling forces in Pareto optimal multi-objective working points. Expert Systems with Applications, 40(6),	http://www.sciencedirect.com/science/article/pii/S095741741201158X

				2312-2322.	
Min-Yang Yang et al., 2002	Optimise feed	Stabilize spindle current	hybrid adaptive control algorithm	Yang, M. Y., & Lee, T. M. (2002). Hybrid adaptive control based on the characteristics of CNC end milling. International Journal of Machine Tools and Manufacture, 42(4), 489-499.	http://www.sciencedirect.com/science/article/pii/S0890695501001389
NuodiHuang et al., 2014	Optimise tool path	Reduce the deformation of the part	a novel method	Huang, N., Bi, Q., Wang, Y., & Sun, C. (2014). 5-Axis adaptive flank milling of flexible thin-walled parts based on the on-machine measurement. International Journal of Machine Tools and Manufacture, 84, 1-8.	http://www.sciencedirect.com/science/article/pii/S0890695514000571
Jirawan Kloypayan et al., 2002	Optimise feed	Stabilize cutting force	a novel method	Kloypayan, J., & Lee, Y. S. (2002). Material engagement analysis of different endmills for adaptive feedrate control in milling processes. Computers in Industry, 47(1), 55-76.	http://www.sciencedirect.com/science/article/pii/S0166361501001361
Ma Peng-yu et al., 2008	Optimise feed, cutting speed,	Stabilize power consumption	a novel method	Peng-yu, M., Yong-biao, H., & Xin-rong, Z. (2008). Research on adaptive power control parameter of a cold milling machine. Simulation Modelling Practice and Theory, 16(9), 1136-1144.	http://www.sciencedirect.com/science/article/pii/S1569190X08001184
M. K. Ki et al., 1994	Optimise feed	Stabilize cutting force	fuzzy logic	Kim, M. K., Cho, M. W., & Kim, K. (1994). Application of the fuzzy control strategy to adaptive force control of non-minimum phase end milling operations. International Journal of Machine Tools and Manufacture, 34(5), 677-696.	http://www.sciencedirect.com/science/article/pii/0890695594900515
Bulent Kaya et al., 2011	Optimise cutting parameters	Reduce tool wear	artificial neural networks (ANN)	Kaya, B., Oysu, C., & Ertunc, H. M. (2011). Force-torque based on-line tool wear	http://www.sciencedirect.com/science/article/pii/S0965997810001663

				estimation system for CNC milling of Inconel 718 using neural networks. Advances in Engineering Software, 42(3), 76-84.	

APPENDIX C List of main CNC controller

Company	Market share of 2012	Products	Adaptive control or not	System requirement	Function block	Memory	Excution cycles	Macro
Fanuc	26%	Series 30i / 31i / 32i		windows	NO	1-8MB	8,4,2,1 ms	√
		Series 35i		windows	NO	Up to 1MB	8,4,2,1 ms	√
		Series 0i		×	NO	Up to 1MB	8,4,2,1 ms	√
		Power Motion i		windows	NO	Up to 2MB	8,4,2,1 ms	√
Haas	14%	EC-300/400/500/1600	Real-time monitoring: tool load Adjust feed rate according to tool load	×	NO	1-750MB	—	√
		ES @ HS		×	NO	1-750MB	—	√
		Series OM		×	NO	1-750MB	—	√
		Series TM		×	NO	1-750MB	—	√
		Series Mini Mill		×	NO	1-750MB	—	√
		Series VF		×	NO	1-750MB	—	√
		Series VS		×	NO	1-750MB	—	√
		Series VF-TR		×	NO	1-750MB	—	√
		Series VF-APC		×	NO	1-750MB	—	√
		Series VF-SS		×	NO	1-750MB	—	√
		Series SR		×	NO	1-750MB	—	√
		Series VM		×	NO	1-750MB	—	√
		MDC-500		×	NO	1-750MB	—	√
		DT-1		×	NO	1-750MB	—	√
HEIDENHAIN	9%	TNC 128		×	NO	1.8GB	3 ms	×
		TNC 320		×	NO	300MB	3ms	×
		TNC 620		windows	NO	1.8GB	3ms	×
		TNC 640	Real-time monitoring:	windows	NO	hard disk>21GB	0.2 ms	×

		ITNC 530	spindle power Adjust feed rate according to spindle power	windows	NO	hard disk>21GB	0.2 ms	×
		CNC PILOT 4290		windows	NO	hard disk>21GB		√
		CNC PILOT 640		windows	NO	1.8GB	0.2 ms	√
SIEMENS	5%	802D sl		×	NO	256KB		×
		808D		windows	NO	1.25MB	12 ms	√
		828D		×	NO	Up to 5MB	0.125 ms	×
		840D sl		windows	NO	9-15MB	0.03125 ms	×
Mitsubishi	4%	M700V		windows	NO	2000KB	—	√
		M70V		×	NO	500KB	—	√
		Series C70		×	NO	Max 2000KB	—	√
		Series 60S		×	NO	230KB	—	×
		Series E60/E68		×	NO	230KB	—	×
		Series C6/C64		×	NO	230KB	—	×
		Series M700		windows	NO	230KB	—	×
		Series M70		windows	NO	230KB	—	×
DynaPath	2.16%	Delta 2000M			NO	—	—	—
OKUMA	2.16%	Series OSP		windows	NO	—	—	—
Mazak	0.96%	MAZATROL MATRIX	Monitoring vibration and reduce vibration of the tool automatically. Monitoring the temperature, vibration and displacement of the spindle.	×	NO	—	—	—
		MAZATROL MATRIX 2		×	NO	—	—	—
		MAZATROL MATRIX NEXUS		×	NO	—	—	—
		MAZATROL MATRIX SMART		×	NO	—	—	—
Aerotech	0.96%	A3200		windows	NO	4GB		×
		Ensemble		windows	NO	2MB	eight motion lines per	×

							1 ms	
		Soloist		windows	NO	2MB	eight motion lines per 1 ms	×
Datron	0.96%	Series M7/8/10		—	NO	—	—	—
		Series M75/85		—	NO	—	—	—
		Series ML1000/1500/1600		—	NO	—	—	—
		Series PR		—	NO	—	—	—
Hurco	0.96%	Series VM		—	NO	—	—	—
		Series VMX		—	NO	—	—	—
		Series DCX		—	NO	—	—	—
Sodick	0.96%	HS150L		—	NO	—	—	—
		HS430L		—	NO	—	—	—
		0LHS65		—	NO	—	—	—

Appendix D Science & Engineering Research Ethics Committee Low Risk Project Submission Form

Appendix F: Guidance on submitting a Low Risk proposal

Science & Engineering Research Ethics Committee

Low Risk Project Submission Form

This form is to be completed by researchers seeking ethical review and approval of research projects involving human subjects and who consider their project to constitute a low risk to their participants. The form is designed to both collect information about your proposed research activities and screen for projects which might be high risk so please complete it carefully.

This form should be completed in full, saved, and emailed to serec@cranfield.ac.uk . If you are a student then your supervisor should review this form before you submit it. You should both provide electronic signatures at the foot of the form. Your submission will be reviewed by one or more members of the Science & Engineering Research Ethics Committee. You will receive an email confirming you can go ahead with the research if it is accepted as a low risk activity.

- SEREC aims to complete reviews of proposals within seven working days of submission.
- Submissions may be approved conditionally with feedback provided to ensure steps are taken to minimise risk to research participants.

Section A

Please provide the following information about your research:

Title of research project or activity	Tool Path Optimisation Based on Function Blocks
Name of researcher(s) conducting the	XIXUAN GUO

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fieldwork		
Email of researcher conducting the fieldwork	x.guo@cranfield.ac.uk	
Name and department of staff member responsible for the work (e.g. Principal Investigator / thesis supervisor)	Dr Jörn Mehnen	
Email of responsible staff member	j.mehnen@cranfield.ac.uk	
Name of research client or sponsor		
Please indicate if the research is part of a:	Taught Masters	☐
	MSc by Research	☑
	MPhil	☐
	PhD	☐
	EngD	☐
	Research Contract	☐
If it is part of a taught Masters programme please give the title of the course		
Intended start date of fieldwork	18th , Feb, 2014	
Intended end date of fieldwork	18th, Apr, 2014	
Who are the intended research participants? (e.g. those who you will be surveying, observing, or speaking to)	Stuff in companies	

Will the research client or sponsor be providing access to research participants?		
No	☑	
Yes	☐	If yes, please provide detail as to how you will ensure anonymity and confidentiality for your participants in the box below:

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We need to fully understand what information/data is being collected from your participants. Please provide a short description (approximately 150 words) of your research aims, objectives and methodology in the box below.

Aim and objectives

Aim

The aim of this research is to create a light-weight optimization programming framework work in function block, the CNC controller will then influenced by the function block to realize the tool path optimization.

Objectives

- Capture the factors, such as feed speed, spindle speed and cutting speed that affect tool path in real-world workshop operation
- Knowledge acquisition on function block and existed rules and algorithms used in tool path optimization.
- Propose a light-weight rule and algorithm which could modelling the relationship between factors and tool path.
- Based on the rule and algorithm, create a light-weight programming framework that can influence CNC controller.

The aim of the questionnaire is to get information from real-world work floor operators and engineers. Their experience will help me to understand how milling operating in real-world. Furthermore, to get information about which factors influence the tool path most. What are the objectives they wish for?

All the information in the questionnaires will be treated confidential and all data will be anonymised.

If you are using questionnaires and/or interview schedules, please ensure that a copy is attached to your research proposal. You will also need to provide a copy of your participant consent form/statement.

Section B

Please answer the following questions to help us evaluate the level of risk associated with your research. If you answer 'Yes' to any of the statements in Section B you should prepare and submit a high risk to SEREC using the guidance provided here

Does your proposed research involve;	
[1]Vulnerable groups such as children, people with physiological and/or psychological impairments (e.g. the disabled, mentally impaired, people with learning difficulties)?	☐ Yes ☑ No
Talking about or referencing sensitive topics (e.g. Sexual behaviour, illegal or political behaviour, experience of violence, abuse or exploitation, mental health, gender or ethnic status conflict situations, psychologically disturbing events?	☐ Yes ☑ No
Questioning or activities which could risk inducing psychological stress, anxiety or humiliation or cause physical pain or harm?	☐ Yes ☑ No
Intrusive interventions - for example, the administration of drugs or other substances, physical exercise, or techniques such as hypnotherapy?	☐ Yes ☑ No
Groups where permission of a gatekeeper is required for initial access to members (e.g. children, residents of institutions)?	☐ Yes ☑ No
The use of payments and / or incentives to encourage or reward participation?	☐ Yes ☑ No
Deception, withholding information, or activities which are conducted without participants' full and informed consent at the time the study is carried out?	☐ Yes ☑ No
Access to records of personal or confidential information, including genetic or other biological	☐ Yes ☑ No

information, concerning identifiable individuals?	
The collection of human tissue or other human biological samples?	☐ Yes ☑ No

[1]If your research involves children or other vulnerable groups; you may need to apply to the Criminal Records Bureau for clearance. Detailed guidance can be found on the CRB website (http://www.direct.gov.uk/crb)

Further details of many of the issues covered in the table can be found in the guidance available on the SEREC website

Section C

Please complete the two tables below using the check boxes on the right hand side. If you cannot confirm all the statements you should prepare and submit a high risk proposal to SEREC using the guidance provided here.

I confirm that as part of the research activity described above;	
I will secure and record the informed consent of all human subjects	☑
I will ensure that no-one is coerced or compelled to participate in the research	☑
I will not use any inducements or incentives to secure participation	☑
I will not use any form of deception as part of the research method	☑
I will explain to participants the level of confidentiality which they can expect and will aim to maintain participant confidentiality wherever practicable.	☑
I will design and execute the research in a way which protects participants from harm (including but not restricted to - physical, psychological, emotional, social, spiritual, career, reputational, financial or legal harm)	☑
I will, prior to any data gathering activity, brief participants about the project	☑

and their rights	
I will, prior to any data gathering activity, brief any individuals involved in data gathering on my behalf (e.g. translators or interviewers) about ethical research practices.	☑
I will, following any data collection activity, debrief participants.	☑
I will not be using any observationally intrusive methods	☑
I will store any data I obtain in accordance with the Data Protection Act	☑
I also confirm that:	
The information I have provided on this form is accurate to the best of my knowledge and belief.	☑
I have read the advice on research ethics contained on the webpage 'Basic principles of ethical research involving human subjects.'	☑
The project described above will abide by the University' s Ethics Policy.	☑
There is no potential material interest that may, or may appear to, impair the independence and objectivity of researchers conducting this project.	☑
Subject to the research being approved, I undertake to adhere to the project description and statements provided above.	☑
I undertake to inform SEREC of any significant changes to the research activity which might invalidate the statements made above	☑
I understand that the project, including research records and data, may be subject to inspection for audit purposes, if required in future.	☑
I understand that personal data about me as a researcher in this form will be held by those involved in the university ethical research review procedure and that this will be managed according to Data Protection Act principles.	☑

The person completing this form is the:

Researcher conducting the work ☑

Supervisor of the project ☐

Electronic signature of the researcher conducting the work 郭石轩

Electronic signature of the project 4th/7/2014

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supervisor

If you have any queries about this form or the SEREC review process, please email the SEREC administrator at serec@cranfield.ac.uk.

Please email your completed form to serec@cranfield.ac.uk

Appendix E Questionnaire of Tool Path Optimisation

Tool path optimisation questionnaire

This Questionnaire is part of MSc research project entitled “Tool path optimisation based on function blocks” aiming to collect information about tool path optimisation.

By participating in this survey, you are consenting for your data to be used for the purpose stated.

Your answers will be treated as confidential and all data will be anonymised.

This questionnaire will last about 10 minutes. Thank you for your participation in this research, your contribution is much appreciated.

Note: Please write the letter of your choice(s) (e.g. A, B, or C …) in the box or write your answer on the line below the question. If other, please list it out.

B.1 General Information

G1. Please choose the type of your company/Institute? (Please choose the most suitable option)

A. Software company
B. R&D Institute
C. Manufacture
D. University
E. Other
Other: __________________________________

G2. What is your job? (Please choose the most suitable option)

A. Software engineer
B. Manager
C. Researcher
D. Operator
E. Programme engineer
F. Student
Other: __________________________________

G3. How long have you worked at this job?

A. Ten years or more
B. Five to ten years
C. Three to five years
D. One to three years
E. Less than one year

G4. Which of the following domains have you ever known about, or have experience on?

A. Computer Aided Process Planning (CAPP)
B. Computer Aided Design
C. Computer Aided Manufacturing
D. Tool path optimisation
E. Programming
F. Function blocks (FB)
Other: ______________________________

B.2 Tool path optimisation

Q1. When creating a tool path what are the main objectives you consider? (choose all that apply)

A. Minimum air cuts
B. Minimum time
C. Minimum tool wear
D. Maximum material removal rate
E. Minimum surface roughness
F. Maximum production rate
G. Minimum power consumption
H. Other: ______________________________

Q2. If more than one objective is considered in your decision how you would prioritise your decision. What is the order in which you rank the objectives you consider?

____

____

Q3. What are the parameters you usually change, from the values given by the tool maker, in order to achieve a good toolpath with respect to the above mentioned objectives?

Parameter	1 (rarely)	2	3	4	5 (usually)
Feedrate					
Cutting speed					
Depth of cut					
Toolpath pattern					
Width of cut					
Coolant					
Other					

Q4. What parameters do you usually fine tune on the controller of the machine?

A. Feedrate
B. Cutting speed
C. Coolant

D. Other: ________________________________

Q5. How do your machine tool operators usually monitor the machining process?

A. Sound
B. Vibration of the machine
C. Spindle load
D. Load on the axes
E. Power consumption
F. Cutting forces
G. Temperature of the workpiece / tool
H. Other: ________________________________

Q6. Would you prefer a fully automated (black box) optimisation algorithm or you would prefer an algorithm with which you could interact and tweak the optimal solution to your preference?

A. Fully automated
B. Interactive

Q7. What is the most important feature a good toolpath has, for use in an industrial level?

____

____

____

Q8. From your experience, Which algorithms are often used?

A. Evolutionary
B. Fuzzy
C. Artificial Neural Networks
D. Particle Swarm
E. Others: ________________________________

Q9. From your experience, what do you think of tool path optimisation? Where the difficulties are?

____

____

____

Q10. Is there any other information you would like to add? ________________________________

____

____

Thank you very much for your participation.

Appendix F result of the questionnaire

Tool path optimisation questionnaire

This Questionnaire is part of MSc research project entitled "Tool path optimization based on function blocks" aiming to collect information about tool path optimization.

This questionnaire will last about 10 minutes. Thank you for your participation in this research, your contribution is much appreciated.

Note: Please write the letter of your choice(s) (e.g. A, B, or C ...) in the box or write your answer on the line below the question. If other, please list it out.
Name (optional): Jose Antonio Rdgz. Cortes
Company/Institute (optional): Prodintec

B.1 General Information

G1. Please choose the type of your company/Institute? (Please choose the most suitable option)

A. Software company
B. R&D Institute
C. Manufacture
D. University
E. Other
Other: ____________________

Answer: B

G2. What is your job? (Please choose the most suitable option)

A. Software engineer
B. Manager
C. Researcher
D. Operator
E. Programme engineer
F. Student
Other: ____________________

Answer: E

G3. How long have you worked at this job?

A. Ten years or more
B. Five to ten years
C. Three to five years
D. One to three years
E. Less than one year

Answer: B

G4. Which of the following domains have you ever known about, or have experience on?

A. Computer Aided Process Planning (CAPP)
B. Computer Aided Design
C. Computer Aided Manufacturing
D. Tool path optimization
E. Programming

Answer: All

F. Function blocks (FB)
Other: ______________________________

B.2 Tool path optimization

Q1. When creating a tool path what are the main objectives you consider? (choose all that apply)

A. Minimum air cuts
B. Minimum time
C. Minimum tool wear
D. Maximum material removal rate
E. Minimum surface roughness
F. Maximum production rate
G. Minimum power consumption
H. Other: ______________________________

A, B, F

Q2. If more than one objective is considered in your decision how you would prioritise your decision. What is the order in which you rank the objectives you consider?

First A, B, F

Q3. What are the parameters you usually change, from the values given by the tool maker, in order to achieve a good toolpath with respect to the above mentioned objectives?

Parameter	1 (rarely)	2	3	4	5 (usually)
Feedrate					X
Cutting speed					X
Depth of cut					X
Toolpath pattern					
Width of cut			X		
Coolant					
Other					

Q4. What parameters do you usually fine tune on the controller of the machine?
A. Feedrate
B. Cutting speed
C. Coolant
D. Other: ______________________________

A

Q5. How do your machine tool operators usually monitor the machining process?
A. Sound
B. Vibration of the machine
C. Spindle load
D. Load on the axes
E. Power consumption

F. Cutting forces
G. Temperature of the workpiece / tool
H. Other: ____________________

A, C

Q6. Would you prefer a fully automated (black box) optimization algorithm or you would prefer an algorithm with which you could interact and tweak the optimal solution to your preference?

A. Fully automated
B. Interactive

B

Q7. What is the most important feature a good toolpath has, for use in an industrial level?

Maintance constant feed per tooth

Q8. From your experience, Which algorithms are often used?

A. Evolutionary
B. Fuzzy
C. Artificial Neural Networks
D. Particle Swarm
E. Others: ____________________

B

Q9. From your experience, what do you think of tool path optimization? Where the difficulties are?

It is necessary incorporate other parameters in the equation (flexion of tool, forces of clamping, final roughness, etc...)

Q10. Is there any other information you would like to add?

Thank you very much for your participation.

Tool path optimisation questionnaire

This Questionnaire is part of MSc research project entitled "Tool path optimization based on function blocks" aiming to collect information about tool path optimization.

This questionnaire will last about 10 minutes. Thank you for your participation in this research, your contribution is much appreciated.

Note: Please write the letter of your choice(s) (e.g. A, B, or C ...) in the box or write your answer on the line below the question. If other, please list it out.
Name (optional): ALEJANDRO
Company/Institute (optional): PRODINTEC

B.1 General Information

G1. Please choose the type of your company/Institute? (Please choose the most suitable option)

A. Software company
B. R&D Institute
C. Manufacture
D. University
E. Other
Other: ______

[b]

G2. What is your job? (Please choose the most suitable option)

A. Software engineer
B. Manager
C. Researcher
D. Operator
E. Programme engineer
F. Student
Other: ______

[C]

G3. How long have you worked at this job?

A. Ten years or more
B. Five to ten years
C. Three to five years
D. One to three years
E. Less than one year

[C]

G4. Which of the following domains have you ever known about, or have experience on?

A. Computer Aided Process Planning (CAPP)
B. Computer Aided Design
C. Computer Aided Manufacturing
D. Tool path optimization
E. Programming

[A, B, C, D, E, F]

X. Function blocks (FB)
Other: ______________________________

B.2 Tool path optimization

Q1. When creating a tool path what are the main objectives you consider? (choose all that apply)

- X. Minimum air cuts
- X. Minimum time
- C. Minimum tool wear
- D. Maximum material removal rate
- E. Minimum surface roughness
- F. Maximum production rate
- G. Minimum power consumption
- H. Other: ______________________________

A, B

Q2. If more than one objective is considered in your decision how you would prioritise your decision. What is the order in which you rank the objectives you consider?

1. Minimum time 2. Minimum air cuts, other objetives depends on part requirments

Q3. What are the parameters you usually change, from the values given by the tool maker, in order to achieve a good toolpath with respect to the above mentioned objectives?

Parameter	1 (rarely)	2	3	4	5 (usually)
Feedrate				X	
Cutting speed				X	
Depth of cut			X		
Toolpath pattern			X		
Width of cut			X		
Coolant		X			
Other					

Q4. What parameters do you usually fine tune on the controller of the machine?

- X. Feedrate
- X. Cutting speed
- X. Coolant
- D. Other: ______________________________

A, B, C

Q5. How do your machine tool operators usually monitor the machining process?

- X. Sound
- X. Vibration of the machine
- X. Spindle load
- D. Load on the axes
- E. Power consumption

F. Cutting forces
G. Temperature of the workpiece / tool
H. Other: ______________________

A, B, C, F

Q6. Would you prefer a fully automated (black box) optimization algorithm or you would prefer an algorithm with which you could interact and tweak the optimal solution to your preference?

A. Fully automated
B. Interactive

B

Q7. What is the most important feature a good toolpath has, for use in an industrial level?

____
____
____

Q8. From your experience, Which algorithms are often used?

A. Evolutionary
B. Fuzzy
C. Artificial Neural Networks
D. Particle Swarm
E. Others: ______________________

Q9. From your experience, what do you think of tool path optimization? Where the difficulties are?

____
____
____
____
____
____

Q10. Is there any other information you would like to add?

____
____
____

Thank you very much for your participation.

Tool path optimisation questionnaire

This Questionnaire is part of MSc research project entitled "Tool path optimization based on function blocks" aiming to collect information about tool path optimization.

This questionnaire will last about 10 minutes. Thank you for your participation in this research, your contribution is much appreciated.

Note: Please write the letter of your choice(s) (e.g. A, B, or C ...) in the box or write your answer on the line below the question. If other, please list it out.
Name (optional): ISMAEL SASTRE
Company/Institute (optional): PRODINTEC

B.1 General Information

G1. Please choose the type of your company/Institute? (Please choose the most suitable option)

A. Software company
(B.) R&D Institute
C. Manufacture
D. University
E. Other
Other: ______

G2. What is your job? (Please choose the most suitable option)

A. Software engineer
B. Manager
(C.) Researcher
D. Operator
E. Programme engineer
F. Student
Other: ______

G3. How long have you worked at this job?

(A.) Ten years or more
B. Five to ten years
C. Three to five years
D. One to three years
E. Less than one year

G4. Which of the following domains have you ever known about, or have experience on?

A. Computer Aided Process Planning (CAPP)
(B.) Computer Aided Design
(C.) Computer Aided Manufacturing
D. Tool path optimization
E. Programming

F. Function blocks (FB)
Other: ______________________________

B.2 Tool path optimization

Q1. When creating a tool path what are the main objectives you consider? (choose all that apply)

A. Minimum air cuts
B. Minimum time
(C) Minimum tool wear
D. Maximum material removal rate
(E) Minimum surface roughness
F. Maximum production rate
G. Minimum power consumption
H. Other: MINIMUM RISK FOR TOOL AND PART

Q2. If more than one objective is considered in your decision how you would prioritise your decision. What is the order in which you rank the objectives you consider?

1° H – 2° E – 3° C

Q3. What are the parameters you usually change, from the values given by the tool maker, in order to achieve a good toolpath with respect to the above mentioned objectives?

Parameter	1 (rarely)	2	3	4	5 (usually)
Feedrate					X
Cutting speed		X			
Depth of cut					X
Toolpath pattern					
Width of cut					X
Coolant	X				
Other					

Q4. What parameters do you usually fine tune on the controller of the machine?
(A) Feedrate
B. Cutting speed
C. Coolant
D. Other: ______________________________

Q5. How do your machine tool operators usually monitor the machining process?
A. Sound
(B) Vibration of the machine
C. Spindle load
D. Load on the axes
E. Power consumption

F. Cutting forces
G. Temperature of the workpiece / tool
H. Other: ____________________

Q6. Would you prefer a fully automated (black box) optimization algorithm or you would prefer an algorithm with which you could interact and tweak the optimal solution to your preference?

A. Fully automated
B. Interactive

Q7. What is the most important feature a good toolpath has, for use in an industrial level?

TIME

Q8. From your experience, Which algorithms are often used?

A. Evolutionary
B. Fuzzy
C. Artificial Neural Networks
D. Particle Swarm
E. Others: ____________________

Q9. From your experience, what do you think of tool path optimization? Where the difficulties are?

Q10. Is there any other information you would like to add?

Thank you very much for your participation.

Tool path optimisation questionnaire

This Questionnaire is part of MSc research project entitled "Tool path optimization based on function blocks" aiming to collect information about tool path optimization.

This questionnaire will last about 10 minutes. Thank you for your participation in this research, your contribution is much appreciated.

Note: Please write the letter of your choice(s) (e.g. A, B, or C ...) in the box or write your answer on the line below the question. If other, please list it out.
Name (optional): Luis Suárez
Company/Institute (optional): PRODINTEC

B.1 General Information

G1. Please choose the type of your company/Institute? (Please choose the most suitable option)

A. Software company
B. R&D Institute
C. Manufacture
D. University
E. Other
Other: ____

[B]

G2. What is your job? (Please choose the most suitable option)

A. Software engineer
B. Manager
C. Researcher
D. Operator
E. Programme engineer
F. Student
Other: Technical staff

[ ]

G3. How long have you worked at this job?

A. Ten years or more
B. Five to ten years
C. Three to five years
D. One to three years
E. Less than one year

[D]

G4. Which of the following domains have you ever known about, or have experience on?

A. Computer Aided Process Planning (CAPP)
B. Computer Aided Design
C. Computer Aided Manufacturing
D. Tool path optimization
E. Programming

[B, C]

F. Function blocks (FB)
Other: ______________________

B.2 Tool path optimization

Q1. When creating a tool path what are the main objectives you consider? (choose all that apply)

A. Minimum air cuts
B. Minimum time
C. Minimum tool wear
D. Maximum material removal rate
E. Minimum surface roughness
F. Maximum production rate
G. Minimum power consumption
H. Other: ______________________

[A]

Q2. If more than one objective is considered in your decision how you would prioritise your decision. What is the order in which you rank the objectives you consider?

____
____
____

Q3. What are the parameters you usually change, from the values given by the tool maker, in order to achieve a good toolpath with respect to the above mentioned objectives?

Parameter	1 (rarely)	2	3	4	5 (usually)
Feedrate			X		
Cutting speed		X			
Depth of cut			X		
Toolpath pattern				X	
Width of cut		X			
Coolant		X			
Other					

Q4. What parameters do you usually fine tune on the controller of the machine?
A. Feedrate
B. Cutting speed
C. Coolant
D. Other: ______________________

[A]

Q5. How do your machine tool operators usually monitor the machining process?
A. Sound
B. Vibration of the machine
C. Spindle load
D. Load on the axes
E. Power consumption

F. Cutting forces
G. Temperature of the workpiece / tool
H. Other: ______________________

A

Q6. Would you prefer a fully automated (black box) optimization algorithm or you would prefer an algorithm with which you could interact and tweak the optimal solution to your preference?

A. Fully automated
B. Interactive

B

Q7. What is the most important feature a good toolpath has, for use in an industrial level?

flexibility, versatility

Q8. From your experience, Which algorithms are often used?

A. Evolutionary
B. Fuzzy
C. Artificial Neural Networks
D. Particle Swarm
E. Others: NO IDEA

Q9. From your experience, what do you think of tool path optimization? Where the difficulties are?

Controlling part and/or tool interferences, minimizing air cut cycles

Q10. Is there any other information you would like to add?

–

Thank you very much for your participation.