Computer Numerical Controlled (CNC) Machining for Rapid Manufacturing Processes

by

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Abstract

The trends of rapid manufacturing (RM) have influenced numerous developments of technologies mainly in additive processes. However, the material compatibility and accuracy problems of additive techniques have limited the ability to manufacture end-user products. More established manufacturing methods such as Computer Numerical Controlled (CNC) machining can be adapted for RM under some circumstances. The use of a 3-axis CNC milling machine with an indexing device increases tool accessibility and overcomes most of the process constraints. However, more work is required to enhance the application of CNC for RM, and this thesis focuses on the improvement of roughing and finishing operations and the integration of cutting tools in CNC machining to make it viable for RM applications. The purpose of this research is to further adapt CNC machining to rapid manufacturing, and it is believed that implementing the suggested approaches will speed up production, enhance part quality and make the process more suitable for RM. A feasible approach to improving roughing operations is investigated through the adoption of different cutting orientations. Simulation analyses are performed to manipulate the values of the orientations and to generate estimated cutting times. An orientations set with minimum machining time is selected to execute roughing processes.

Further development is carried out to integrate different tool geometries; flat and ball nose end mill in the finishing processes. A surface classification method is formulated to assist the integration and to define the cutting regions. To realise a rapid machining system, the advancement of Computer Aided Manufacturing (CAM) is exploited. This allows CNC process planning to be handled through customised programming codes. The findings from simulation studies are supported by the machining experiment results. First, roughing through four independent orientations minimized the cutting time and prevents any susceptibility to tool failure. Secondly, the integration of end mill tools improves surface quality of the machined parts. Lastly, the process planning programs manage to control the simulation analyses and construct machining operations effectively.

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List of Abbreviations

Acronyms	Definition
3DP	Three Dimensional Printing
ABS	Acrylonitrile Butadiene Styrene
Add-O	Additional Orientation
AM	Additive Manufacturing
API	Application Programming Interface
ArcHLM	Arc Hybrid-Layered Manufacturing
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CAPP	Computer Aided Process Planning
CAT	Computer Axial Tomography

Acronyms	Definition
CNC	Computer Numerical Control
D	Dimension
EBM	Electron Beam Melting
EDM	Electrical Discharge Machine
FDM	Fused Deposition Modelling
GUI	Graphical User Interface
HisRP	High Speed Rapid Prototyping
Ind-O	Independent Orientation
IPW	In-process Workpiece
LENS	Laser Engineering Net Shaping
MCS	Machine Coordinate System
MIG	Metal Inert Gas
MRI	Magnetic Resonance Image
MRR	Material Removal Rates
RDVC	Relative Delta Volume Clearance
RM	Rapid Manufacturing

Acronyms	Definition
RP	Rapid Prototyping
RP&M	Rapid Prototyping & Manufacturing
RPTM	Rapid Prototyping, Tooling and Manufacturing
RT	Rapid Tooling
SiC	Silicon Carbide
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SPI	Society of the Plastics Industry
SRP	Subtractive Rapid Prototyping
STL	Standard Tessellation Language
TAV	Tool Access Volume
UAM	Ultrasonic Additive Manufacturing
WEDM	Wire cut Electrical Discharge Machine

List of Symbols

Symbols	Definition/Units
%	Percentage
µm	Micro metre
^{0}	Angles
mm	Millimetres
θ	Input angle

Symbols	Definition/Units
mmpm	Millimetres per minute
Ø	Diameter
rpm	Revolutions per minute
Θ	Range on visibility orientation

CHAPTER 1

INTRODUCTION

1.1 Research overview

In recent years, the goals of manufacturing systems have become more intense due to global competition in product development. In order to reach the market quickly, products need to be manufactured within time frames that are commonly used to produce prototypes (Koren 2010). Consequently, this trend has attracted the attention of technology developers to improve the current manufacturing methods employed in making prototypes. Historically, rapid prototyping (RP) technologies were introduced in the 1980s and were used to quickly create prototypes in an automated manner. The main purpose of this group of technologies was to assist new product development particularly for analysis and evaluation processes. RP allows design changes at early phases of product development and confirms validity of the product before entering full scale production. As RP technologies have evolved, their role has expanded to produce finished parts or end-user products. Instead of being used just for conceptualization, the advancements of technology have empowered the process to produce high specification products such as moulds and tooling, customised parts and biomedical components (Yan et al. 2009, Eyers et al. 2010, Campbell et al. 2012). Hence, several new terminologies have been introduced to reflect the evolution of the technology which includes rapid manufacturing (RM), rapid tooling (RT) and rapid prototyping and manufacturing (RP&M).

In order to establish RP technology as a reliable manufacturing method, several different techniques have been developed and commercialized. Most of the techniques have been developed based on an additive mechanism that builds the part by stacking layers of material (liquid, powder or sheet) until the entire object is formed (Wohlers 2008). Further developments have invented some advanced techniques that are capable of processing metallic materials instead of just producing polymeric products. Using more powerful energy sources such as electron beams, the part is constructed by melting and joining layers of material, maintaining the additive mechanism. This is recognized as an additive manufacturing (AM) process which is intended to handle RM and RT applications. However, as the technology continues to evolve and process requirements become more complex, AM faces several difficulties in coping with the high demands of manufacturing end-user products. Currently, the process is still struggling to resolve several limitations that restrict its abilities. Even the technology capable of processing metallic materials, may not be able to fully cater for several important issues which include roughness, accuracy, manufacturing materials and final part properties (Campbell et al. 2012, Wong et al. 2012). Most research work has been only focused on improving AM processes or materials, neglecting other methods that could be adopted for RM applications.

On the other hand, direct manufacture of metal parts is one of the key indicators for the process to be used in RM applications. Qualitative assessment of various processes that are capable of producing metal parts is presented in Figure 1.1. According to this diagram, only two processes are capable of directly fabricating metal parts. The rest can be considered as indirect processes because they use other methods such as moulds and dies to actually produce the parts. Since the limitations of AM processes remain unsolved, alternative methods need to be considered for RM such as cutting operations. However, there is a limitation in terms of part complexity despite the capability to handle low to medium production quantities. This method of manufacturing is categorized under subtractive processes. Essentially, further investigation is required to explore the capability of this method in RM processes.

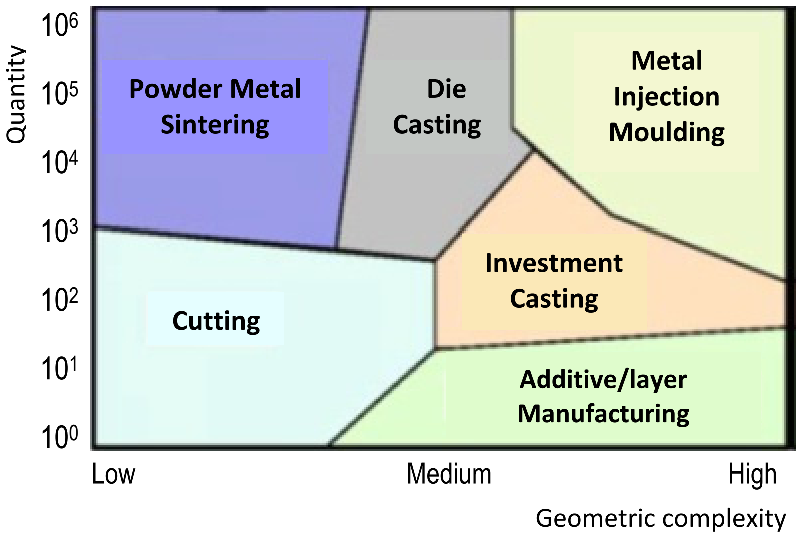


Figure 1.1: Qualitative assessment of different processes in producing metal parts (Levy et al. 2003)

Subtractive rapid prototyping (SRP) is a conventional technology that has been previously used to create prototypes. In general, the term subtractive means the process of removing material away from the workpiece to form physical objects (Burns 1993). Traditionally, the cutting process utilizes hand tools to shape the materials and produce the part. Later, the introduction of CNC technology has improved the process with the capability of performing different kinds of machining operations. This technology was developed before the introduction of various AM processes. However, due to the attractive features of AM processes namely their easy of operation, increased design freedom, high automation and speed of production, the development of CNC machining has been left behind and has not been fully considered for RM applications.

In terms of process capabilities, CNC machining employs a different mechanism in building the part which is totally opposite to AM processes. Cutting tools are used to penetrate and remove material from the workpiece. Hence, a great variety of denser and stronger materials such as pure metals can be directly machined. In addition, greater part accuracy and superior surface finish are among the interesting features promised by CNC machining processes. Unfortunately, all these benefits do not in themselves fully justify the implementation of CNC machining for rapid processes.

There are several factors that limit the ability of CNC machining to be incorporated in RM processes. The central issue relies on the absence of rapid machining systems to assist in the setup planning before executing cutting operations (Frank 2007). Unlike AM processes, CNC machining requires a proper process plan that primarily involves the development of cutting toolpaths. Many variables need to be defined in the planning stage including cutting parameters and tool sizes. A common solution is to leave all the decisions to the skilled machinist in order to develop an effective machining program. As a result, the planning tasks are highly dependent on human inputs and this restricts process automation which is an important part of the requirement for a rapid system. Another limitation can be seen in terms of the approach to fixturing and tooling. If the part possesses intricate and complex features, special tools and fixturing methods are required to develop the geometries. In the case of re-fixturing the part, the coordinate system must be setup again. These time consuming activities still limit the performance of CNC machining even though it is capable of surmounting many of the inherent limitations presented by AM processes.

Recent developments in the application of CNC machining for rapid processes have led to a renewed interest in adopting this technology. A novel approach known as CNC-RP manages to use the subtractive process in RP&M applications. The CNC-RP methodology utilizes a conventional 3-axis milling machine with two opposite 4th axis indexers and is able to machine parts from various cutting directions (Frank et al. 2002). Machining from different orientations is proven to expand the accessible regions and allows the creation of parts with complex shape. Since various materials can be machined with high precision and accuracy, this process is suitable for making ordinary prototypes, tools, customised parts or any components for small production runs. Prototypes that possess similar material properties as in full scale production will enable real validation and testing processes. But, the application of CNC-RP goes far beyond component testing. CNC machining is capable of fabricating tools that can be used for mass production. Similarly, it also can produce final parts especially for more demanding applications with tight requirements. The capability of CNC machining to produce parts directly from Computer Aided Design (CAD) models will bring the product to market sooner with minimum development cost (Rosochowski et al. 2000).

This thesis proposes and evaluates further improvements in CNC-RP methodology and is specifically focused on making the process compatible to RM applications. In the global market, other than producing new products with minimum cost and time, it is also necessary to achieve high quality (Lan 2009). Therefore, there are two crucial aspects that can be considered process requirements. First, the production time which includes both time spent in the process planning and part fabrication must be kept to a minimum. Thus, process automation and optimization are the key solutions to fulfil this requirement. RM processes are specifically used to produce final parts that will be directly delivered to the user. Hence, quality attributes become a major concern and must be enforced on the part produced. This can be seen in terms of accuracy and surface integrity. In order to propose the improvements, further investigations on the process methodology are carried out.

1.2 A glimpse of CNC-RP

Generally, three distinct developments based on cutting orientations, toolpath planning and fixturing approaches have succeeded in establishing rapid machining using CNC processes. The use of indexing devices allows the workpiece to be rotated to various angles. In order to determine sufficient cutting orientations, visibility analysis is performed on the part prior to the machining processes (Frank et al. 2006). The output of the analysis is a minimum set of orientations that allows the cutting tool to reach the entirety of the part surfaces. Hence, all geometries that are visible from at least one of the orientations can be completely machined. Within each cutting orientation, roughing and finishing operations are performed one after another (Frank 2007). Several requirements need to be obeyed during cutting operations that are basically related to cutting levels and machining sequences. Once completed, the workpiece is rotated to the next orientation that reveals new surfaces to be machined. During this process, the workpiece remains on the indexing device and thus preserves the original coordinate system, hence eliminating the rework of further setups. The processing steps in CNC-RP are visualized in Figure 1.2.

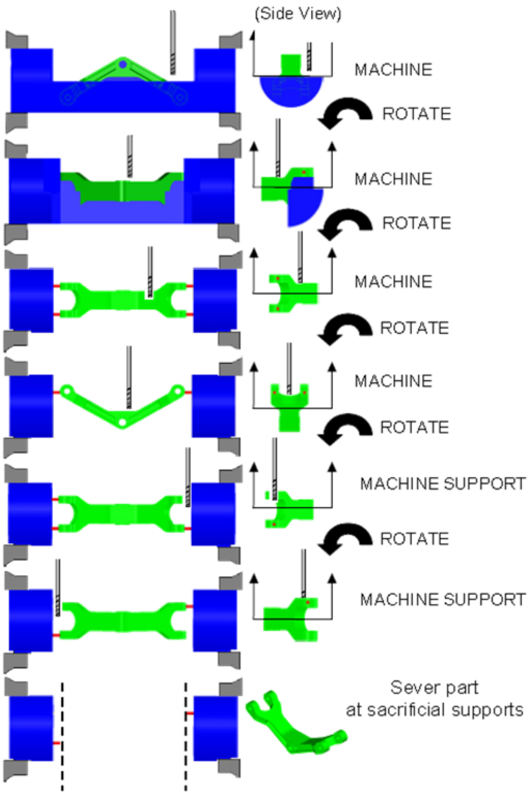


Figure 1.2: Processing steps in CNC-RP (Wysk 2008)

CNC-RP employs a feature free approach which does not consider any features that may be present on the part. Therefore, universal toolpath planning is adopted that simply machines all surfaces on the part. The smallest tool diameter is selected in finishing operations with the aim of reaching all part geometries (Frank 2003). Most of the cutting parameters are standardized for both roughing and finishing operations. Some of the decisions may not be the most favourable for machining operations, but, it allows the rapid generation of toolpaths and fulfils the requirements for RM processes. The fixturing method employs the addition of small diameter cylinders parallel to the axis of rotation at both ends of the part. These supports are machined simultaneously with the part and remain connected to the workpiece once machining has been completed. These sacrificial supports must be then removed during later post processing. Most of the tasks performed in CNC-RP are assisted by customised algorithms that are incorporated in commercial Computer Aided Design/Computer Aided Manufacturing (CAD/CAM) packages.

1.3 Problem statement

Implementation of CNC machining in RM processes requires different approaches that contradict common practice. The nature of machining processes involves considerable human input to control and run the operation. This is different from other RM tools such as AM processes that tend to have less human involvement and are fully automated during production. In order to incorporate CNC machining in RM processes, new approaches have been developed which manage to adopt extensive levels of automation in the processing steps. However, there are several issues with current implementations that cause inefficiency and limitations to the process. In general, this can be perceived from three different perspectives that relate to cutting orientations, tooling approach and process planning.

The integration of a 3-axis milling machine and 4th-axis indexers for CNC-RP preserves some flexibility in the system to rotate the workpiece to various orientations. As illustrated in Figure 1.3, different cutting directions possess different levels of accessibility. Therefore, an algorithm is developed to assess the surface visibility of the part from different directions (Frank et al. 2006). Basically, the main purpose of visibility analysis is to determine the necessary cutting orientations to fully machine the part. Hence, the orientations proposed are meant to be effective during the last stage or in finishing operations that guarantee tool accessibility to all surfaces (Renner 2008). In early developments, only a single operation is performed within each cutting orientation. Later development introduced separated operations where a rough cut is performed first followed by a finishing process within the same orientation. So, instead of removing the bulk of the material, the finish cut just needs to remove the remaining material not accessible to the roughing tool.

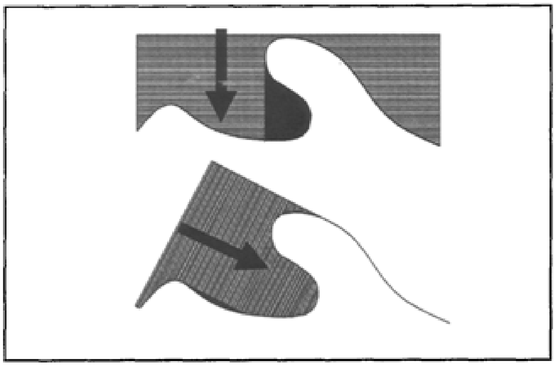


Figure 1.3: Cutting tool accessibility (Frank et al. 2004)

During roughing operations, the cutting tool needs to remove a large amount of material and penetrate the workpiece until the maximum cutting depth is reached and this is dependent on the tool length. The condition of this machining is visualized in Figure 1.4. This is a part of the requirement to prevent the formation of thin material (thin webs) during the subsequent cutting orientations which is an undesirable situation in machining. Another method to avoid this problem is by machining with at least three cutting directions.

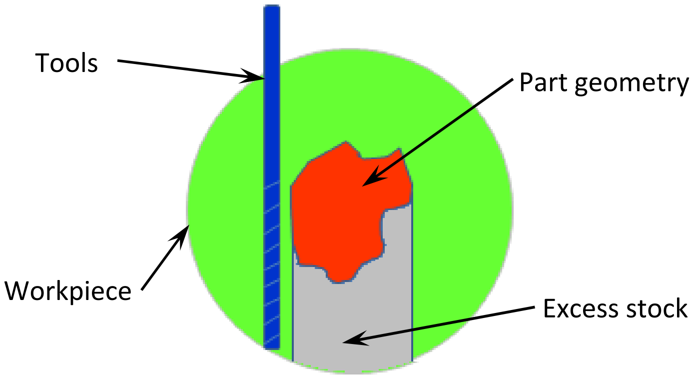


Figure 1.4: Long cutting depth adopted by CNC-RP (Frank 2007)

There are two issues that can be investigated based on current implementations. First, constraining roughing operations to cutting orientations also used for finishing processes tends to limit the possibility of optimising the process. Therefore, instead of relying on the orientations proposed by visibility analysis, roughing operations can be performed at different angles that aim for high volume removal and minimum machining time. So far, however, no research has been found that attempts to optimise the roughing operation in order to improve overall process efficiency. Since the process is highly dependent on part geometries, this serves as an alternative approach to cutting the workpiece from various orientations.

The second issue is related to the cutting level employed in the roughing operation. The drawbacks of this decision can be seen in terms of tool usage and selection. Cutting operations involve physical contact between the tool and workpiece. One of the factors that effects tool performance is the contact length which will influence flank wear and tool temperature (Sadik et al. 1995). Hence, a long tool contact length can easily cause a deflection due to the cutting forces generated. Without appropriate control of machining parameters, the cutting tool is subjected to bending, distortion and chatter during machining. All these phenomena directly affect the quality of the machined part. In CNC-RP, process continuity between each orientation is paramount. Any tool breakage will interrupt the coordinate system including tool location and leads the whole operation to fail. One of the tool requirements for this operation is to have sufficient flute length to keep the tool close to the part and excess stock. This tends to cause restrictions in the selection of a tool as a long cutting tool is not commonly used and available. Therefore, the determination of cutting levels in this process needs to be revised. However, far too little attention has been paid to minimizing the cutting levels due to the requirement of thin web avoidance rules.

The tooling approach in CNC-RP is quite straightforward. Originally, the selection of cutting tools is just based on the smallest diameter available for the predetermined length that depends on workpiece size (Frank et al. 2002). Hence, the depth of cut is set at a minimum to achieve the required surface finish. However, neglecting some important parameters has resulted in inefficiency during the machining operations. For example, using a single tool size simplifies the toolpath development but the trade-off of this decision is a slow rate of material removal. Therefore, roughing operations are proposed to counter this inefficiency problem. The tool size is selected based on a linear relationship with the workpiece diameter. In addition, a flat end mill is commonly used to machine the part since the process relies on 2D cross sectional slices of the model (Frank 2003). Therefore, a staircase effect is developed on part surfaces as can also commonly be seen in AM processes. But, the capability of CNC machining to cut at very shallow depths minimizes the appearances of stepping.

In CNC machining, the development of cutting toolpaths is carried out by a CAD/CAM system. It is undeniable that these systems are capable of assisting in toolpath generation but the task of determining the type and size of cutting tool is usually overlooked (Veeramani et al. 1997). Recent developments have succeeded in proposing an optimum tool size combination by using several optimization tools (Renner 2008). However, to date, there are no clear guidelines to integrate different types of cutting tools into the process. This integration is important since in one cutting orientation, different kinds of surfaces are presented on the 3D object. Hence, using a flat end mill to machine non-flat surfaces is not really efficient as it obviously causes a staircase appearance as shown on Figure 1.5.

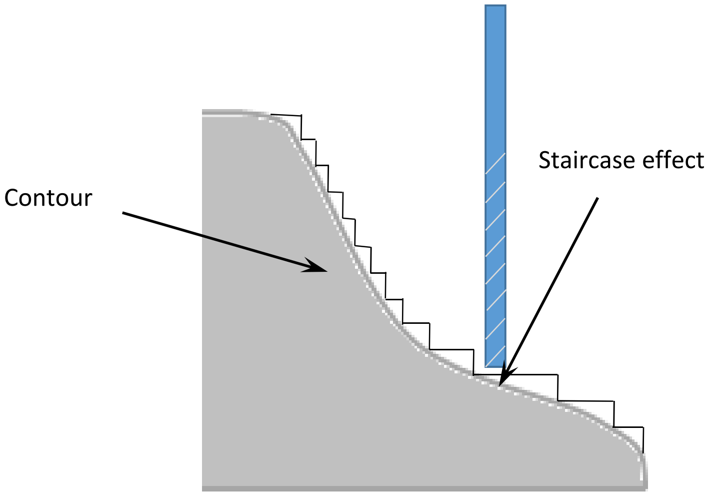


Figure 1.5: Staircase effect on contoured surfaces

Process planning in CNC machining deals with large amounts of data and requires support tools to optimise the operation. This is one of the factors that make some consider CNC process planning to be primarily a manual task (Anderberg et al. 2009). The planning task in CNC machining is crucial and directly correlated to the time, skill and cost to machine discrete parts (Frank 2007). Therefore, an efficient machining plan is usually developed through experience by skilled CAM operators (Frank et al. 2006, Relvas et al. 2004). From a production perspective, it is important to minimize the time spent in producing parts. However, from the perspective of rapid processes, the time spent on both planning and production must be kept to a minimum. Therefore, the generation speed of toolpaths and faultless machining codes needs to be increased. This is a key indicator that will determine the applicability of CNC machining in RM processes (Qu et al. 2001). The existence of Computer Aided Process Planning (CAPP) systems manages to minimize the time allocated for planning tasks. However, CAPP systems need to be developed correctly in order to produce effective machining operations. Previously, CNC-RP has preserved a certain level of automation in process planning. Hence, most of the tasks executed in the planning stage are well-assisted and established as a rapid machining system. In accordance with the automation requirement, any new approaches introduced to improve the machining operation must definitely be equipped with the planning tools to assist the development stage.

1.4 Aims and objectives

The aim of this research is:

“To strengthen the implementation of CNC machining in RM processes (CNC-RM) by improving the machining and tooling approach at the same time establishing a rapid machining system”

Further investigation of current implementations of CNC machining in rapid processes has revealed several inefficiencies in the methodology. The problems discussed in section 1.3 have clarified the gaps found in the present approaches. Hence, there are two main objectives formulated to tackle the issues raised.

Objective 1: Investigate a different strategy to improve roughing operations by manipulating cutting orientations.

1.4.1 Rationale of objective 1

Roughing operations are performed in CNC machining to remove the bulk of material from the workpiece and to generate the profile of the part. In the metal cutting industry, roughing operations are considered to be time consuming processes and can take up to 50% of the total machining time depending on the size of workpiece and part (Kuragano 1992). Since roughing and finishing operations are directly correlated, removing the bulk of the material in the first place will assist the rest of the cutting processes in finishing operations. This justifies the need to develop a proper plan for an optimum material removal process during the roughing stage. Nevertheless, a common practice in rough cutting is still employed using larger tool sizes and aggressive cutting parameters to shape the part.

Particularly in RM application, the roughing operation is supposed to be executed in the orientations that provide maximum removal volume rather than maximum surface areas. The orientation proposed by visibility analysis is totally concerned with achieving maximum surface areas so that all features are accessible by the cutting tools. Hence, finishing operations are the most likely suitable process for these orientations. On the other hand, establishing other orientations for roughing operations might be useful to improve the machining efficiency. This approach tends to increase the number of orientations which contradicts previous studies that prefer to have minimum orientations (Frank et al. 2006). But, considering an automatic indexing device is used, the rotation task can be controlled directly from the machining code. The key parameters to validate the approach are time spent to machine the part and also the effectiveness of the sequence of operations. In order to generate these parameters, virtual machining simulation is utilized to handle the analysis. An approach to determining orientations is required that possesses maximum roughing time, minimum cutting time and fulfils the cutting condition requirements.

Objective 2: Investigate the influence of different cutting tools and formulate the integration approach to be implemented in CNC-RM processes

1.4.2 Rationale of objective 2

Improving part quality in RM processes has become a major concern for manufacturers. The parts produced must exhibit the same properties and dimensional tolerances as those produced by conventional manufacturing methods such as CNC machining (Zhao et al. 2000). Previous developments that adapted CNC machining for rapid processes were capable of fulfilling this requirement. However, limited tool selection during finishing operations has restricted the ability of this process to fabricate superior quality products. Aiming for process planning simplification, there is no clear method developed to integrate different cutting tools in finishing operations. In 3-axis machining, a flat end mill possesses the capability to machine flat regions that can be represented as horizontal or vertical surfaces. However, due to the limitations in machining axes, this tool is not suitable for machining other kinds of surfaces such as free form or sculptured surfaces. As the flat end mill is the tool most likely to be adopted, the staircase appearance will be present on the machined part and this affects surface quality. This situation leads to the investigation of implementing different types of cutting tools in CNC-RM processes. Primarily, the implications can be observed through the excess volume and surface roughness of the machined parts.

A variety of tools are available in CNC machining to allow the process to handle different part surfaces. Additionally, this technology is equipped with automatic tool changing systems which can be controlled directly from coded instructions. So, incorporating different cutting tools in the machining operations would not be a problem to the system. Nevertheless, in the CNC-RM application, critical attention is required in assisting the cutting area selection within and between each of the orientations. The aim is to provide flexibility in cutting tool selection and at the same time meet the automation requirement in the planning stage. However, the nature of machining processes requires different tools to effectively machine different part features. Therefore, a universal approach needs to be developed so that the planning process can be executed rapidly and be applicable to different parts. In order to formulate the solution, the medium of interaction between the user and CAM system needs to be established. Enhancement of CAM systems permits integration with any independent program files to execute specific tasks (Miao et al. 2002). With this ability, customised programs can be used to control the machining operations development in the planning stage. Hence, the user can generate toolpaths based on different machining regions using suitable cutting tools.

1.5 Thesis outline

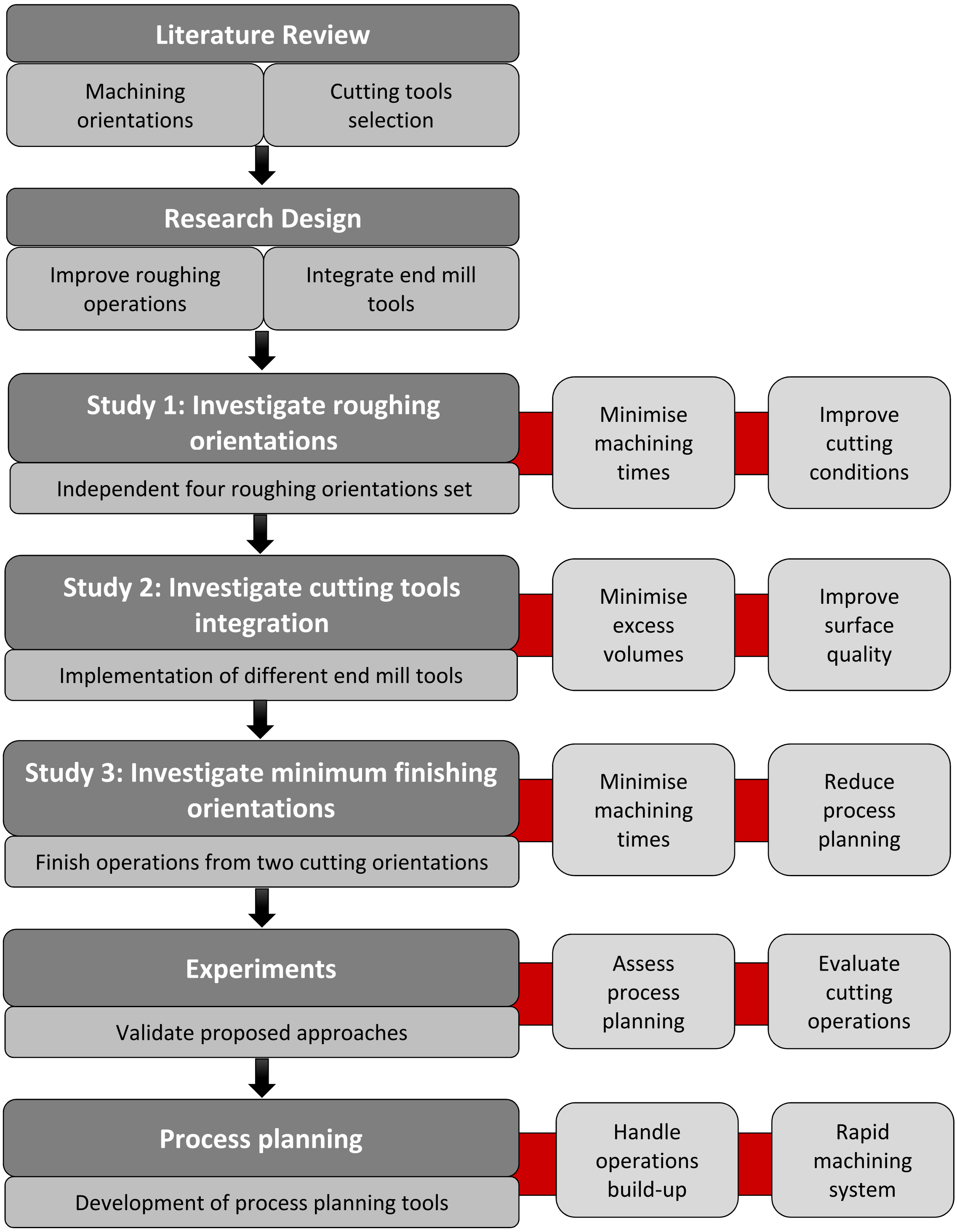


Figure 1.6: Structure and outcomes of the work

The thesis has been organised in the following way:

Chapter 1: As described in the previous sections, this chapter provides a brief insight into RP technology and the evolutions that enable the process to manufacture end-used products. It also introduces a distinct method of using CNC machining to perform rapid processes. Several inefficiencies in the approach are discussed which are later used to formulate the research objectives. The last section highlights the contributions of this study and benefits to manufacturing technology.

Chapter 2: The literature review begins by laying out previous developments related to RP processes. Numerous techniques are described based on the additive and subtractive processes. Next, a few sections cover the improvements that have been carried out in each of the processes including the introduction of CNC-RP methodology. This is the method that successfully incorporates CNC machining with rapid processing. Then, the entire review sections are specifically focused on the development of CNC-RP including recent improvements that aim to overcome process limitations. Lastly, a critical comparison is conducted between additive processes and CNC machining. Limitations and advantages of each process are reviewed mainly to strengthen the argument for implementing CNC machining for RM applications.

Chapter 3: Before executing real developments, preliminary studies were performed to validate the proposed approaches. The studies attempt to portray the objectives of this research. Therefore, the first section discusses possible methods to improve the roughing operations. The second section relates to an investigation of machining in terms of the effects of different cutting tools on three part surfaces; flat, inclined and freeform. Appropriate tools to execute planning tasks are explored in the last section. Several instructions in CAM software are translated into a programming language and the codes are analysed.

Chapter 4: This chapter describes the work that has been performed to improve roughing operations in CNC-RM processes. Different methods are proposed based on additional and independent cutting orientations. Then, the implementation of each method is conducted virtually through a series of machining simulations assisted by a CAM system. Finally, the implications are analysed and the method that fulfils the assessment criteria is proposed as an optimum way to determine a set of roughing orientations.

Chapter 5: Detailed implementation of different types of tools in finishing operations is described in this chapter. Basically, the methodology section describes surface classification, tool selection and verification processes. Simulation analysis is the primary method used to validate the approach. Hence, the results are based on the machining time and excess volume left on the part. This is a part of the quality attributes that can be extracted from virtual analysis.

Chapter 6: This chapter explains other potential benefits that might be obtained by integrating the proposed approaches. Therefore, the effects of machining non-complex parts from two cutting orientations are investigated. On each of the tested models, the results include machining times and excess volumes. These will influence the decision whether or not to incorporate two cutting orientations in the planning system.

Chapter 7: All the approaches developed are further verified in this chapter by fabricating physical parts using a CNC machine. The methodology section represents the cutting parameters adopted for each part and the preparation before starting the machining operations. The results section contains two main parts that report on the simulation and machining outcomes. Machining simulations are carried out to construct the cutting operations based on approaches developed in this research. Then, during the machining stage, real machining times are verified followed by the roughness analysis on the part surfaces. To extend the discussion, problems raised whilst conducting the experiments are highlighted and the feasible actions to resolve them are provided.

Chapter 8: The planning systems developed to assist the analysis and to build machining operations are reported in this chapter. The first part presents the basic approach adopted in developing the system. Then, the two main systems are introduced, one to find an optimum orientations set for roughing operations and the other used to handle tools integration and completely produce machining codes. The capabilities and effectiveness of the systems are verified by processing seven tested models that are different in terms of geometry, size and shape.

Chapter 9: All the work discussed in the thesis is summarized in this chapter. The findings of the studies that have been conducted are highlighted. Moreover, the limitations and recommendations of this thesis are also included to provide direction for future improvements that will further establish the CNC-RM process.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

For the past several decades, rapid fabrication methods have significantly influenced a revolution in manufacturing processes. In the early introduction phase, rapid prototyping (RP) was the technology used to assist in new product development, particularly in building prototypes. The method allows the analysis and evaluation processes to be conducted on a physical model. Furthermore, any changes can be made at the early stages of product development and the technology is proven to minimize the time consumed. According to the process flow in new product development, it is feasible to improve the part in the early stages of development as the cost of doing so is low and there will be few implications for downstream processes. Several advances, especially in additive processes, have resulted in this technology being implemented for producing end-use products and the term has been upgraded to rapid manufacturing (RM) (Driscoll 2008, Eyers et al. 2010). These distinct advantages have resulted in considerable attention by industry to implement the technology. Nevertheless, RP technology is still struggling to cater for various issues such as part quality and accuracy, materials, processing methods and cost. Further enhancements are necessary and it is thought that other established manufacturing methods such as machining can be adapted for the RP and RM applications. The structure of the reviews conducted in this chapter is shown in Figure 2.1. The review starts with a fundamental understanding of the nature of the RP and RM technologies. The discussion is then expanded to view several processes that are based on additive (AM) and subtractive methods. After this, other technologies developed to execute rapid processes are reviewed. The next part of this chapter describes the crucial area of the current state of implementing CNC machining for RM processes. This is followed by the improvements that have been carried out to strengthen the method. Finally, distinctions between the AM and CNC machining methods are discussed by assessing several characteristics that have been highlighted from the past research.

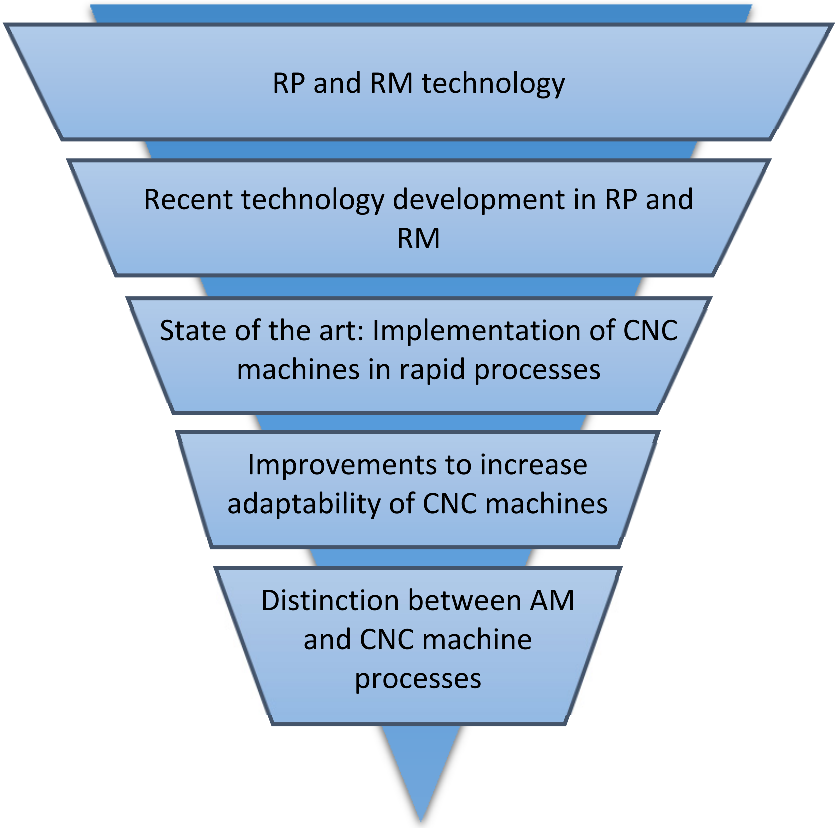


Figure 2.1: Structure of literature review

2.2 Rapid prototyping and manufacturing technology

2.2.1 General terminology

RP can be described as a group of techniques used to produce three-dimensional products from numerical descriptions such as models from CAD. The technique exhibits distinct characteristics with its quick operation, automation and high flexibility (Noorani 2006). Historically, RP was introduced in the 1980s and triggered a revolution in product design and development (Karunakaran et al. 2000). The first technology introduced led to enormous interest from other groups which later proposed several other innovative methods for RP purposes. Therefore, the applications have been expanded to other areas which are described by other terms such as rapid prototyping, tooling and manufacturing (RPTM) (Chua et al. 2010). Most of the terms are developed to address a specific area of application. RM is used when the process is capable of manufacturing final products rather than just prototypes. Since the part is directly fabricated, the application of RM is mostly suitable for low-volume production. The term rapid prototyping and manufacturing (RP&M) is used to describe the integration of both technologies. Figure 2.2 shows several other terminologies used to represent RP processes.

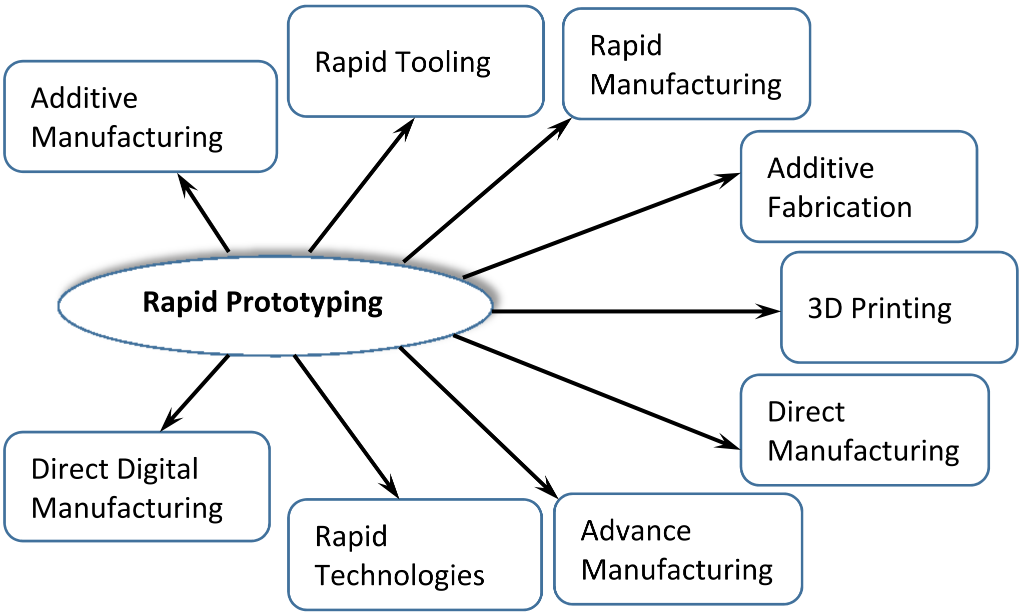


Figure 2.2: Terminologies of rapid prototyping (Fischer 2013)

There is a common interest between all the technologies developed for RP which are aimed at producing accurate parts in the shortest possible time and with less human intervention. Generally, the benefits of RP technologies can be seen from different perspectives. First, they provide opportunities for designers to physically interpret their design and allow verification processes to be carried out. From the designer's perspective, prototypes can be used for two different purposes: to evaluate the aesthetic values and to test the functionality of the parts

(Lennings 2000). Therefore, prototypes can be divided into two different types. The first is a styling model which is used to evaluate the artistic value of the parts. The exterior representation is very important and a reliable manufacturing process is required to build the part. The second type is based on functional prototypes which are expected to endure forces during testing and accurately meet the specified dimensions of the part. In this case, machining is a reliable method to build the prototype as it can process robust material and produce high quality parts (Salloum et al. 2009).

On the other hand, RP also enhances the effectiveness of communication between various departments in industry. The nature of a prototype which is easy to interpret enhances the cross-linking communication and information sharing between different parties. Moreover, this technology has also renewed the way of carrying out product development. By decreasing cost and development time, it allows engineering changes and modifications to be made during early design phases. This prevents the waste of resources and undesirable corrections at later stages when the part is ready for manufacture. Furthermore, it also compresses the tasks involved in product development and can be executed in a parallel manner. Referring to Figure 2.3, the time and cost for product development can be minimized by up to 50% compared to traditional sequential approaches (Chua et al. 2010).

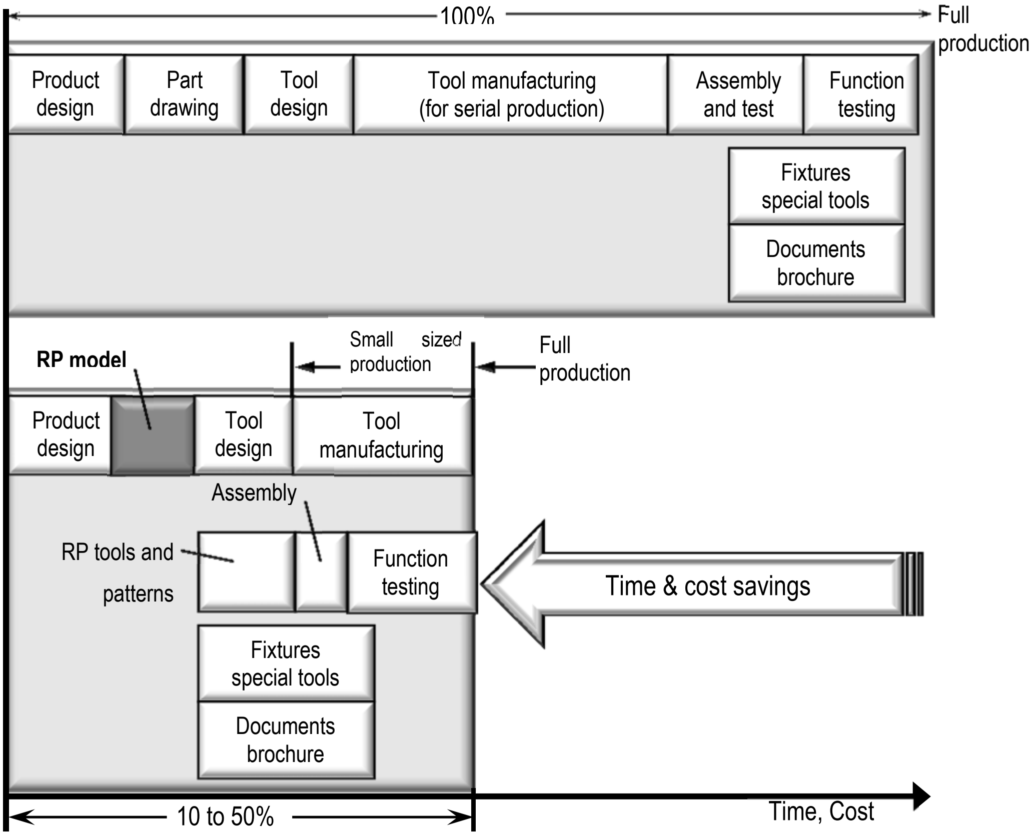


Figure 2.3: RP technologies in product development (Chua et al. 2010)

As illustrated in Figure 2.4, Onuh et al. (1999) classify manufacturing methods into three distinct processes that are based on subtractive, additive and formative methods. Under each process lie several methods that manufacture parts using different techniques but still rely on one of these basic processes. Subtractive processes manufacture parts by removing the material from workpiece. Several methods can be used such as CNC machining, laser cutting, electron beam machining and water jet machining. On the other hand, formative processes utilize force and pressure to create an object. Among the methods are electromagnetic forming and adaptive die casting. Meanwhile, additive processes build the part on a layer basis until the final geometry is achieved. Basically, most of the methods in the additive process category are recognized as RP technologies. Other methods within the subtractive and formative categories are not considered as RP tools due to the several limitations. However, recent developments have improved CNC machining capabilities in this respect and potentially the method can be adopted for the RM application. The next section will describe RP methods developed within the additive and subtractive categories.

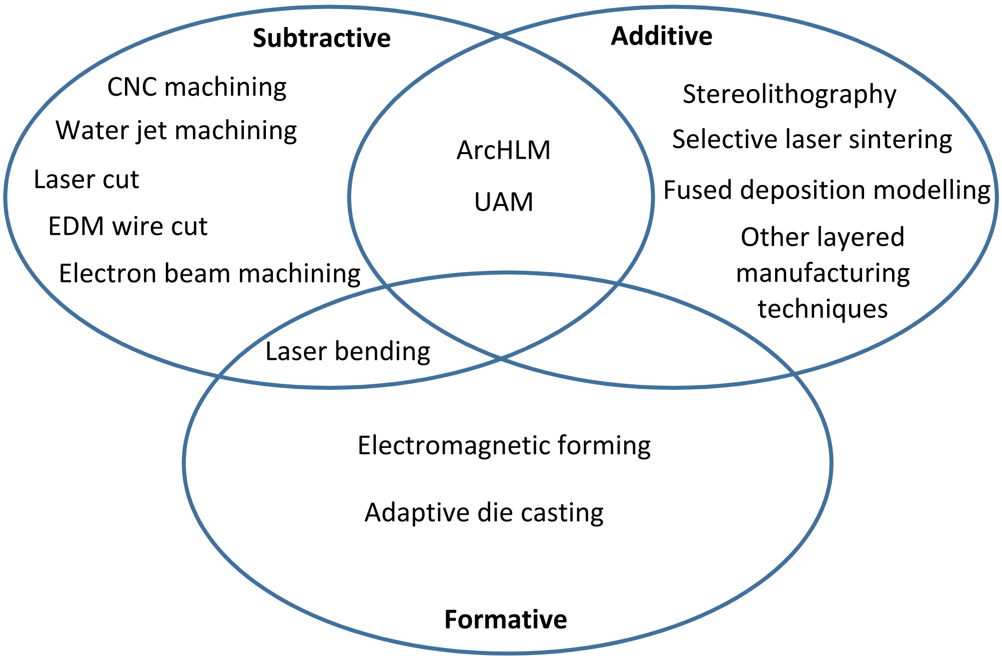


Figure 2.4: Fundamental of manufacturing processes (Onuh et al. 1999)

2.2.2 Additive processes

The fundamental aspect of additive processes is the building up of a part by stacking two and half-dimensional “2½ D” cross sectional layers of the model (Boonsuk et al. 2009). These stacking operations are executed until the entire shape of the part is completely formed. Generally, most commercial RP technologies can be classified as additive processes. There are several common steps adopted in the RP process to build the part. First, a solid model is created using a commercial CAD software package such as AutoCAD, NX, Solid Works and many other systems. There are other methods that can be used to build the model such as Magnetic Resonance Image (MRI) scanning, Computer Axial Tomography (CAT) scanning and by the use of data generated from a digitising system (Upcraft et al. 2003). The model represents the complete geometry of the part including interior and exterior features. Next, the CAD model is converted into STL (Standard Tessellation Language) file format. The conversion translates the 3D model into a collection of triangular facets. If necessary, some adjustments are carried out to repair the converted file so that the representation is close to the original object. Now the model is ready to be created using any RP technology. Beginning with empty space, thin layers of material are stacked continuously. Depending on the methods used, the model is completed through post processing that could possibly include cleaning and post curing. Figure 2.5 visualizes typical workflow in RP systems.

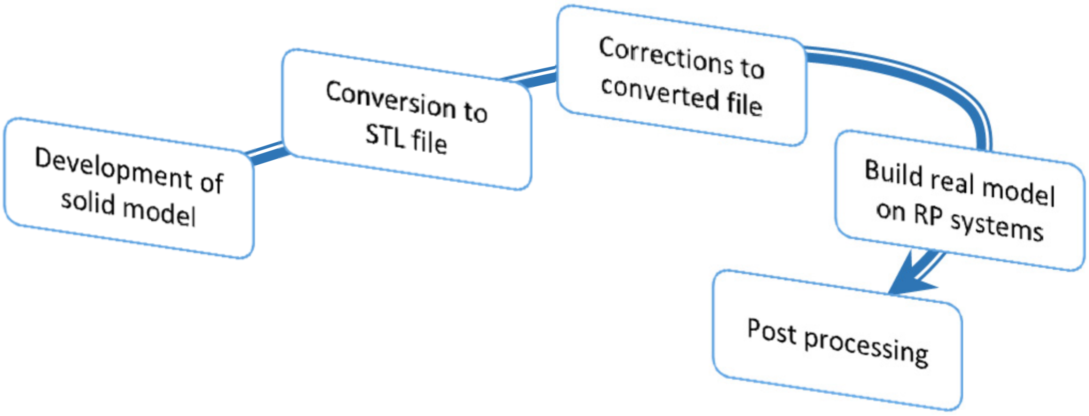


Figure 2.5: Common process flow in additive processes (Noorani 2006)

There are numerous RP technologies developed that adopt additive processes. Basically, these technologies can be simply categorized by referring to the original form of the materials used to build the object (Chua et al. 2010). There are three main categories of RP technologies which consist of liquid-based, solid-based and powder-based systems. Each of these categories is described in the next sub-section with examples of methods that have been successfully implemented and widely used.

2.2.2.1 Liquid-based systems

These processes create physical models from a liquid state which undergoes a curing operation to harden the material. A well-known process is stereolithography (SLA). This process can be regarded as a founding RP technology and it operates based on the reaction between liquid resin and a laser beam (Yang et al. 2009). The parts are built by controlling the solidification of a liquid resin using a computer-controlled laser beam (Melchels et al. 2010). Within each layer, the laser traces a predetermined path over the resin and causes the liquid to solidify to a defined depth. The structure of the machine consists of a platform capable of vertically movement to which a vat containing the liquid resin is attached. Once the first layer solidifies, the platform moves downwards typically about 0.1mm and a new thin layer of liquid resin will flood the model. The process is repeated until the finished part is produced. Figure 2.6 shows a schematic diagram for SLA processes. In order to create overhanging features, a support structure is used which later needs to be removed. Post curing is performed once the build process has been completed. The parts are placed inside an oven for a few hours depending on the volume to remove the remaining liquid and partially cured resin.

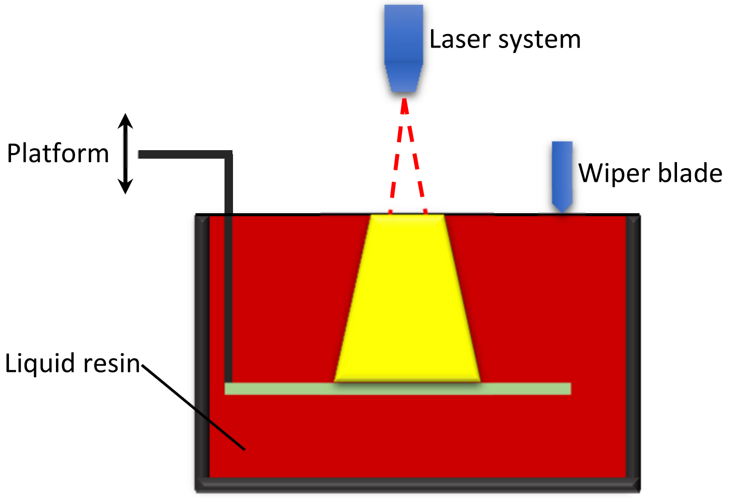


Figure 2.6: Schematic diagram of SLA processes

The SLA process is quite advanced in terms of accuracy and resolution compared to other additive methods. It can construct an object with accuracy up to 20 µm while other methods are typically only capable of achieving about 50 to 200 µm. Depending on the process parameters, the roughness values (R_a) of the part produced are between 1 and 5 µm. Additionally, the part can have a tacky surface and possess a certain level of brittleness. Post curing processes are required to completely harden the resin. This process needs proper control as if it is cured for too long the part is liable to warp. Generally, the applications of SLA are not limited to conceptualization and modelling only, but can also be extended to produce patterns for casting and tooling design.

2.2.2.2 Solid-based systems

The use of a solid form of material to build the part is a common feature of all methods in this category. Fused Deposition Modelling (FDM) is a typical example of the process. FDM builds the part by precisely depositing the material from an extruder or nozzle in the form of thin layers (Zein et al. 2002). The extruder is equipped with temperature control mechanisms to semi-melt the thermoplastic filament material and deposit it onto the platform. Upon completion of one layer of the part, the platform is lowered ready for the next deposition process. Among the materials used are polyester, Acrylonitrile Butadiene Styrene (ABS), elastomers and investment casting wax. Generally, a proper cooling of material is achieved by heating it to 0.5^{o}C above its melting point which later causes the material to solidify 0.1s after it has been deposited. One of the important parts of the machine equipment is the extruder. This device moves horizontally in X and Y directions and carries two different nozzles. The first is used to extrude the part material whereas the second nozzle deposits the support material to hold overhang features. Figure 2.7 shows a typical configuration for the FDM process.

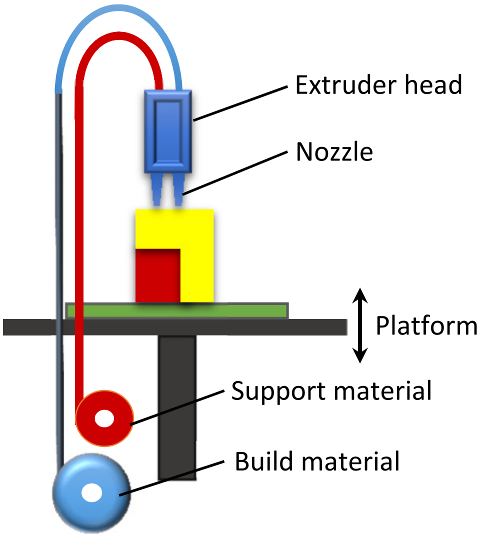


Figure 2.7: Schematic diagram for FDM process

During the building process, attention is required for few parameters such as consistency of nozzle speed, material deposition rate and speed of the plotter head (Pham et al. 1998, Au et al. 1993). Having proper control of these parameters will ensure that a high quality part is produced. FDM processes can be regarded as a desktop prototyping facility. Generally, the attractive features of this process are its reliability, straightforward part build-up and capability to process a wide range of thermoplastic materials (Masood 1996, Masood et al. 2004). Moreover, the materials used are less expensive, toxic-free and safe for the environment. ABS is a typical material and produces parts that have 85% of the strength of plastic parts produced by injection moulding. Therefore, this process is well-known for producing functional prototypes which can be used for assembly and testing purposes. The final part can achieve roughness (R_a) of approximately 10 to 15µm if the layer thickness is set around 0.178 to 0.254mm (Kattethota et al. 2006). However, the surface finish is still dictated by the filament size used and causes restrictions in the accuracy. The other causes that affect the accuracy are shrinkage and deflection. Due to the rapid cooling of the deposited material, the proper control of process parameters is critically important.

2.2.2.3 Powder-based systems

The production of powder-based components can be considered as making a substantial contribution in the development of RP technology. Several methods have been devised including Selective Laser Sintering (SLS). This technology is powered by a carbon dioxide laser beam that heats and fuses powdered polymeric materials in layers to build the whole object (Tan et al. 2003). SLS machines consist of two powder supply chambers which are located on both sides of the platform (Figure 2.8). The building process starts by heating the platform to below the melting point of the material which facilitates the fusion between the layers and minimizes thermal distortion. A 25-100W powered laser beam is used to trace a layer of powder which represents a cross section of the part. Once the layer has been sintered, the platform is lowered and the chambers rise to supply the material. The roller then spreads the powder to create a new layer and the laser tracing process is repeated (Król et al. 2013).

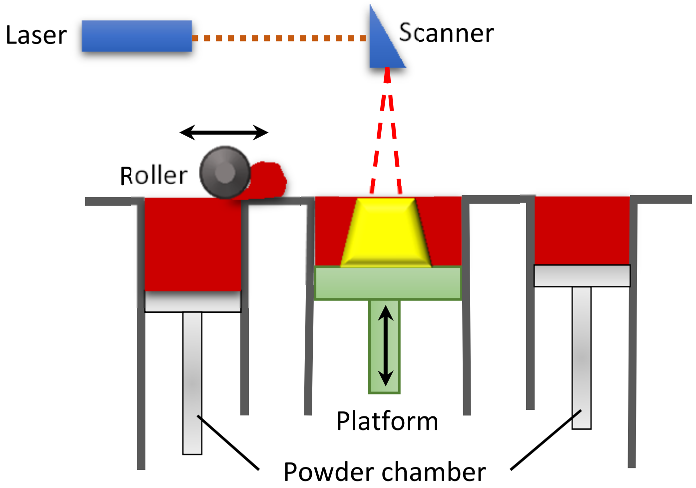


Figure 2.8: Schematic diagram of SLS process

The application of SLS has been extended to RT and RM as it has the ability to process different materials (Kruth et al. 2005). Overhanging features do not require any support structure and this eliminates the time required to build and remove support structures. Since a sintering mechanism is utilized, the achievable roughness is around 7 to 10µm. There are a few drawbacks including high power consumption and a long cooling cycle. The laser must be powerful enough to allow the sintering process to take place between the powder particles. The high temperatures involved in building the part means that a cooling down period is required before the part can be removed on completion of the process. Large particles of powder may lead to poor surface finish and porosity.

Another favourable process in this category is three dimensional printing (3DP). The process operates in similar way to the ink-jet printing process where thin layers of powdered material are joined by a selectively sprayed binder material (Suwanprateeb 2007). This technology is recognised as a high speed process because of the binding method used rather than the melting and solidification of powder that results in longer processing time (Wohlers 2001, Bak 2003). On top of this, it is also considered as a low cost RP system which has a strong influence on the application of the technology (Dimitrov et al. 2006). A major drawback is that the parts built by this method are fragile and need proper handling. Furthermore, post processing is frequently needed to improve surface finish and increase bonding strength.

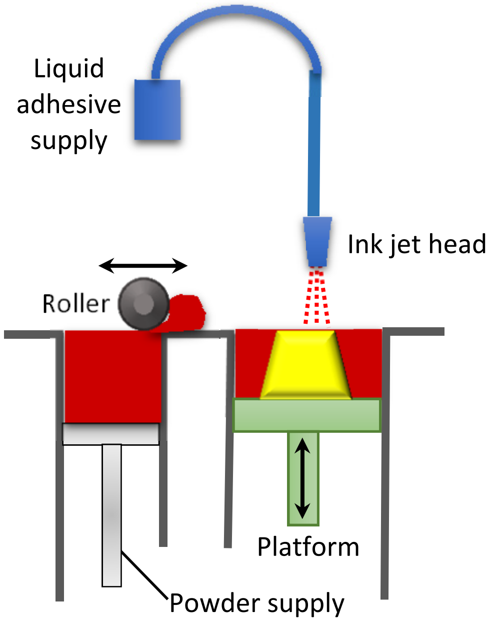


Figure 2.9: Schematic diagram of 3DP process

2.2.3 Subtractive processes

Subtractive processes operate in the opposite way to additive processes in that the material is cut away from the workpiece instead of adding material gradually to build the part. The material removal process can be performed by cutting a small portion of the workpiece using any kind of tool. Traditionally, hand tools are most likely to be used to perform the cutting process and in this case it totally depends on human skill. Later, the introduction of CNC technology in cutting machines has enhanced subtractive manufacturing and brought the technology to a mature phase. The CNC technology has improved the automatic capabilities of various cutting machines such as in milling, laser cutting and high speed machining.

A CNC milling machine can be a reliable alternative technique for the RM application. It employs a subtractive process, shaping a block of material by cutting off chips until the entire shape of the model is formed (Lennings 2000). However, most previous researchers did not recognize milling and turning machines employing CNC technology as a RP technique (Frank et al. 2003). The main obstacles that prohibited this method from becoming RP process are due to pre-process engineering and setup planning (Akula et al. 2006, Frank et al. 2010). However, it is undeniable that CNC machining possesses the highest degree of accuracy and repeatability. The finishing operation can afford up to 0.0127mm accuracy which is far and away better than other regular AM processes. Moreover, the machine is capable of processing a wide range of materials and thus manages to produce fully functional parts.

As of today, the introduction of hybrid RP systems that combine subtractive processes alongside AM processes have demonstrated the need for CNC machines to improve the operations. Several other benefits are expected to be obtained by implementing CNC machining as a RM process. The most attractive feature of this process is the ability to handle a wide range of materials from soft materials like foam board up to hard materials such as steel. Large machines can accommodate larger parts and make it suitable for example for producing aerospace components. Accuracy levels can be chosen and this provides full control based on the process requirements.

Nevertheless, CNC machining is still constrained by the automation issue particularly in the planning stage before cutting operations start. Commonly, planning tasks are executed through CAM systems. The 3D model is transferred to a CAM system where the cutting toolpaths are developed to achieve the desired accuracy and surface finish. Prior to that, several cutting parameters and strategies need to be defined and these closely rely on the skill of CAM operators to produce optimum cutting operations. The process flow of Figure 2.10 shows the typical steps employed to execute machining processes. The red block represents a critical stage of the planning process in machining. There are also other factors that influence the machining quality including cutting strategies, process parameters, tool positioning and networking communication (Akula et al. 2006).

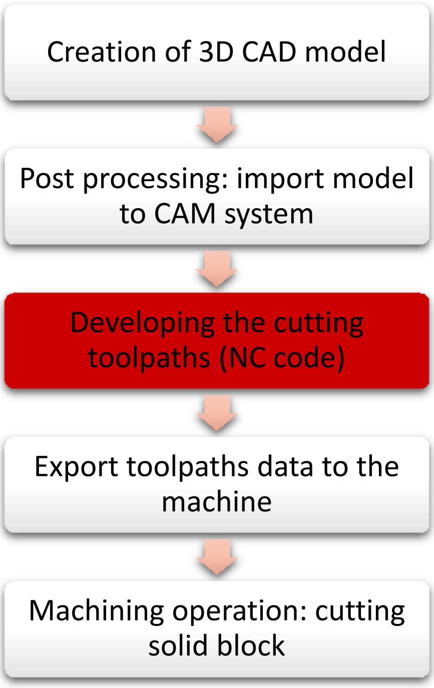


Figure 2.10: CNC machining process flow (Nikam 2005)

2.2.4 Section summary

The evolution of RP technologies has brought several new terminologies to address the process. However, the nature of the process is preserved with the aim to produce parts rapidly with less human involvement. The previous sections have clearly pointed out several techniques developed to perform RP operations. These techniques are classified based on additive and subtractive processes. In additive processes, the creation of a part is based on adding a layer of material until the final shape is formed. The techniques created within this category can be grouped into liquid, solid and powder based. Due to the layer mechanism employed, this process is capable of creating almost any shape or feature including complex and sophisticated parts. Moreover, parts can be directly created from virtual models with minimum processing, an important consideration as planning tasks are usually time-consuming. However, the limitations of this process can be seen in terms of part quality and material availability.

On the other hand, subtractive processes generally can be represented by CNC machining operations, based on material removal processes that shape the workpiece to become a part. Depending on the machine capabilities, this process provides excellent control of accuracy and surface finish. Various cutting tools can be used and thus allow the machine to process different kinds of materials. The primary task of the subtractive process is removing the material based on predetermined paths. Therefore, extensive work is required during the planning phase which is time consuming and requires manual intervention.

2.3 Developments in rapid prototyping and manufacturing technology

2.3.1 Production of metallic parts

The capability of producing complex parts with endless geometric features is one of the remarkable strengths of AM processes. However, additive technologies are still struggling with the materials processing abilities that prevent it from manufacturing real parts. In recent times, AM has gone through series of developments enabling it to be extended into specific application areas. Modification of processing tools and methods has permitted AM to process metal-based materials. Several researchers have recorded the success of AM processes in producing customised parts for medical applications (Poukens et al. 2010, Heinl et al. 2008, Murr et al. 2012). The medical implants are produced in the same manner as basic additive processes which build up on a layer basis. However, processing biocompatible materials such as titanium and cobalt chromium requires high energy sources. Thus, advanced processes such as Electron Beam Melting (EBM) are employed. This process utilizes an electron beam to scan a layer of metal powder causing the particles to fuse and join. The operations are performed inside a vacuum chamber to provide a controlled environment for the electron beam. The nature of EBM processes has led to the production of highly pure materials with reasonable strength properties.

Laser-based additive manufacturing is another method that can be used to produce metallic parts. Among the well-known processes are Selective Laser Melting (SLM) and Laser Engineering Net Shaping (LENS). Both processes utilize laser beams to fully melt powders. During the development of the part building processes, a combination of small grains, non-equilibrium phases and new chemical compounds has led to better mechanical properties (Kumar et al. 2011). Accuracy for both processes is around 50 to 100µm and achievable roughness is typically less than 10µm. There are similarities between SLM and SLS in terms of processing apparatus and operations, but the difference is the mechanism of bonding between the particles. In SLM, the substance is fully melted to create a completely dense part that can achieve 99.9% density without any post processing operations (Gu et al. 2012).

Meanwhile, the LENS process utilizes high powered laser beams to melt the metal powder that is supplied by the deposition head. Hence, the melting materials are deposited on selective locations to build an object. This technology can be extended to life-cycle engineering for the refurbishment or modification of parts. However, from the production perspective, high consumption of energy leads to economic issues. Advanced processes have empowered AM to cater for the production of metallic parts. Overall, it manages to improve the density of the parts but still there are some implications for quality and accuracy. This tends to limit the processes from being adopted in manufacturing operations.

2.3.2 Hybrid processes

Generally, hybrid processes integrate additive processes with subtractive processes in one single workstation. With the evolution of RP to RM applications, the combination of these two processes makes a substantial contribution to making tools and discrete parts. From the process planning point of view, additive processes are fast and automatic systems promising an easy way to produce prototypes. On the other hand, CNC machining offers high accuracy, good finishing and the processing of a wide range of materials. Therefore, the combination of these processes is significant in meeting the requirements for next generation production systems. Figure 2.11 describes the advantages gained by integrating the processes

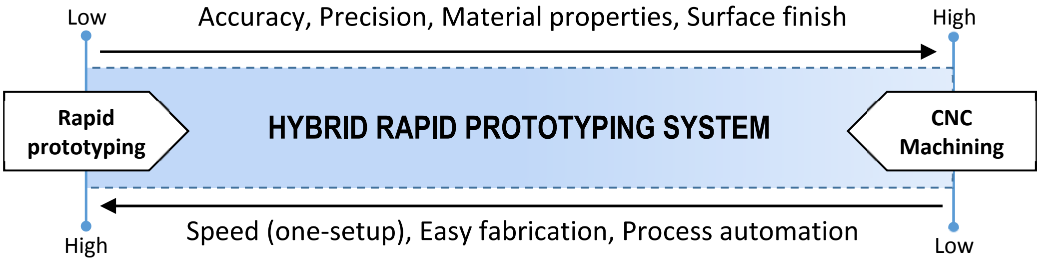


Figure 2.11: Additive and subtractive combination (Hur et al. 2002)

Implementation of RM technology for pattern manufacturing has benefited the process especially for short production runs. Luo et al. (2010) proposes a method of stacking a piece of material followed by machining operations to shape the model on the particular layer. The process of stacking and machining the material is repeated until the final shape is achieved. The slabs of material used on each layer are not necessarily uniform. In fact, normally they are divided adaptively based on part features and considering the machining operations to shape the layer. Generally, the machining is used to level the layer to a certain height and to control the appearance of assembly lines between the layers. Figure 2.12 indicates the basic operations executed in this hybrid process. Consequently, this hybrid approach allows the making of large deep patterns and small features. It also simplifies the machining planning from the complete large part to the small individual layers. Hence, machining can be performed using short and small diameter tools.

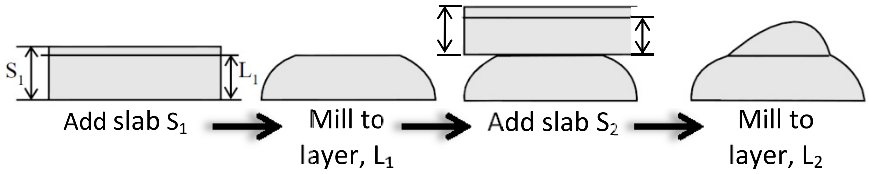


Figure 2.12: Rapid pattern manufacturing processes (Luo et al. 2010)

Known as hybrid-layered manufacturing, the integration of welding (material deposition) and machining processes (material removal) has broadened the combinations and is not only restricted to common AM processes. Welding is recognized as a joining process that fuses the materials by melting the workpiece and adding filler material to form a strong joint. The adding material mechanism has introduced the possibility of adapting the welding process to build parts. Initially, 3D welding systems were developed in the early 1990s and were capable of building simply shaped components (Dickens et al. 1992, Spencer et al. 1998). This system utilized robotic control of a welding torch to assist the deposition of material rapidly in specific locations to build metal parts. Proper control of weld bead and the cooling process will guarantee consistency of part properties.

Further developments have improved 3D welding systems by integrating the process with machining operations. The method proposes the use of the Transpulse Synergic Metal Inert Gas (MIG) welding process for near-net layer deposition and CNC milling for net shaping process (Karunakaran et al. 2000). After one layer has been deposited, roughing and finishing operations are executed. Masking material is applied if the part requires a support structure. The irregularity of the arc welding process will possibly cause a defect between the layers. Therefore, a face milling operation is performed within the layers to prepare the surfaces for the next layer deposition. This process is improved by introducing heat treatment before machining is executed to relieve stress and increase strength (Akula et al. 2006). Later on, a new development involved retrofitting the welding torch unit to an existing CNC machine which realises the creation of parts at a single workstation (Karunakaran et al. 2009). This hybrid system is known as Arc Hybrid-Layered Manufacturing (ArcHLM). Figure 2.13 shows a set of dies use to test the effectiveness of the processes. Moreover, the system also promotes total automation across the building and shaping stages in addition to more economic and faster processes.

There is also another type of welding process used as a basis of hybrid system development. Ultrasonic Additive Manufacturing (UAM) is a process that is based on solid state welding operations to combine multiple thin foil layers together by using ultrasonic welding. The process starts by placing new foil on the previous layer. Before the welding process is executed, the foil is tacked down to form a light joint. Then, the layers are joined using high ultrasonic energy that causes the metal to bond together. The mechanism of joining is based on plastic flow of the material and no melting occurs (Schick 2009). These processes are repeated with subsequent layers. The CNC machine is used to final shape the part and removes excess material once the layer building process is complete. In addition to the production of complex parts, UAM is capable of joining different materials as well as object embedding such as Silicon Carbide (SiC) fibres and stainless steel wire mesh in an alloy 3003 matrix (Ram et al. 2007). Therefore, this technology has increased the variety of materials that can be produced and expands the area of engineering applications.

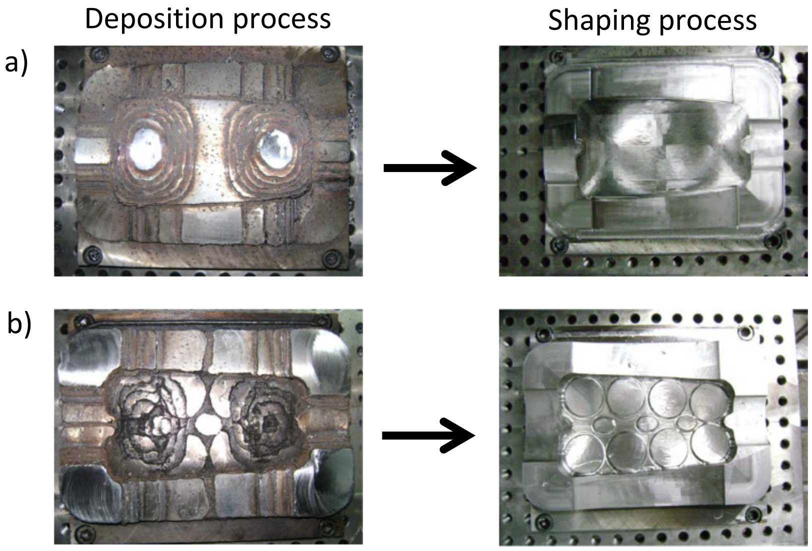


Figure 2.13: (a) cavity and (b) core manufactured through ArcHLM processes (Karunakaran et al. 2009)

In order to expand the advantages of hybrid technology, the process combinations have been expanded and do not only represent combinations of different processing groups (additive and subtractive). Several other processes within the same group can be controlled simultaneously and interact with each other to realise a hybrid manufacturing system. For example, a laser beam can be used to soften the material prior to being machined by the cutting tool in a turning process (Shin 2011). The combination of these technologies is proven to improve the process efficiency and prolong cutting tool life. Lauwers et al. (2014) have reviewed several other developments including vibration assisted grinding, laser assisted bending and the combination of stretch bending with an incremental forming process. In general, the implementation of hybrid processes in manufacturing improves process capabilities and minimises the limited application of individual techniques.

2.3.3 Development of subtractive processes for RM applications

Instead of integrating different processes, RM is possible by relying on subtractive processes only. An established material removal process such CNC machining offers distinct capabilities to transform 3D virtual models into physical objects. Despite the low cost of operation, CNC machining promises reliable geometry accuracy and surface quality by alleviating the staircase effect on the part surface (Yang et al. 2002). This process is also capable of catering for an extensive range of materials (Tut et al. 2010). Owing to these abilities, machining based RM is well-qualified in the tooling and customised parts production.

One of the methods developed utilizes high-speed milling for rapid application and this process is known as HisRP (Shin et al. 2003). Conventional fixturing methods that use a vice to hold the workpiece tend to cause obstructions to machining the entire surface of the part. Hence, HisRP utilizes an automatic fixturing approach that uses low melting point metal alloy to hold a complex workpiece. This alloy fills the cavity left from front face machining and serves as a fixture to hold the part for another machining process on a different surface. Eventually, this RM system manages to reduce manufacturing time and product cost. However, additional processes are required to melt and pour the metal alloy within each orientation setup. Basically, the processing steps of HisRP are summarized as follows:

Step 1: Holding workpiece on an automatic setup device

Step 2: Cutting operations executed using high speed milling machine

Step 3: Fill the cavity produced with low melting point metal alloy

Step 4: Rotate the workpiece to start new machining orientation

Step 5: Cutting performed to cater for the other half of the workpiece

Step 6: Melting away the metal alloy once the part is completely machined

Another subtractive process utilizes a non-traditional machine to produce RM parts. The advantages of Wire cut Electrical Discharge Machine (WEDM) are exploited for RT applications. Consequently, a distinct technology called

WirePATH^{TM} has been developed to assist the processing steps (Lee 2005, Lee et al. 2003). The principle of mould development using this technology is by assembling part segments that have been precisely machined. Consequently, the results indicate a reduction in cost and processing time where the mould can be produced 40-70% faster than conventional methods. There is also another process that uses a similar machine but a different methodology. A WEDM-RP wire cut EDM machine is used to manufacture complex parts efficiently while at the same time eliminating the manual tasks in process planning and programming (Yang 2010). The system utilizes a global tangent visibility algorithm to generate the setup plan and wire path. This serves as a medium for automation in the process planning and supports the implementation in a rapid environment. High accuracy products can be manufactured regardless of how hard the material is because WEDM is a free force process that penetrates the workpiece through controlled sparks.

CNC milling is an established machining process that is proven to be useful in producing a wide range of products and meeting the quality requirements. Therefore, it is worthwhile considering the adoption of this technology in machining-based RM to create prototypes as well as final parts. The CNC-RP technology employs layer-based toolpaths from different cutting directions to completely machine parts without any re-fixturing task (Frank et al. 2002). This process is carried out using a 3-axis CNC milling machine with an indexable 4th axis device that clamps and rotates the workpiece. During the planning stage, the method adopts a feature-free approach in order to simplify the tasks and minimize human intervention. Without doubt, CNC machining is highly suited for producing tooling and customised parts. Therefore, the proposed method has intensified the potential of CNC machining which previously was constrained by planning and automation issues.

2.3.4 Section summary

The trends in RM are to continually seek better part quality, diversity of materials and process simplifications. Therefore, various methods have been introduced in RM systems to satisfy the demands and surmount the problems raised. Progress has been recorded in upgrading the additive processes to produce metallic parts. Several technologies such as EBM, SLM and LENS have been briefly described. As a result, the properties of the parts are improved and the diversity of materials used is increased. But, part quality and accuracy are still issues. Subsequently, the section also discussed hybrid technologies that attempt to pool the advantages of both additive and subtractive processes. Generally, hybrid systems manage to accommodate the weaknesses presented by additive processes. The integration improves part quality and allows rapid production of metallic components. However, the systems require complex process planning due to the different processes. The equipment cost is high and thus it becomes less sensible for use in small and medium size production. Recent developments in subtractive processes, particularly in CNC machining, has strengthened the position of this process in RM applications. A certain level of automation can be assimilated in the planning phase and thus speed up the process of producing machined parts. Considering this, it is beneficial to concentrate on improving the capabilities of CNC machining processes so that they become one of the prominent RM tools.

2.4 CNC machining for RP&M

Limited material selection and accuracy in additive processes has promoted the use of CNC machining in RM processes. On the other hand, the part geometry freedom is reduced but considering the quality and process capabilities, this technology is still a viable process to produce discrete components. The widespread use of CNC machining for RM has been constrained by the nature of the manual process planning that is required. Fortunately, recent developments have created a novel approach in adopting the CNC machining process for RP&M purposes which is known as CNC-RP.

2.4.1 Overview of CNC-RP

CNC-RP is a distinct methodology developed to produce prototypes through subtractive processes. This method employs layer-based material removal from several machining orientations on a part that is fixed in one axis of rotation (Frank et al. 2003). Using a conventional 3-axis vertical machining centre, all surfaces of the part are machined without the need for re-fixturing. The re-orientation of the workpiece is carried out by using two opposing fourth axis indexers. Figure 2.14 visualizes the mechanism of machining and fixturing in CNC-RP. In order to impart some level of automation in the process planning, a feature free machining approach is adopted. It is important to find general solutions that permit automation while employing CNC machining for RP&M applications. Therefore, a single universal plan is developed which is adaptable to machine all components regardless their shapes and geometries (Petrzelka et al. 2010).

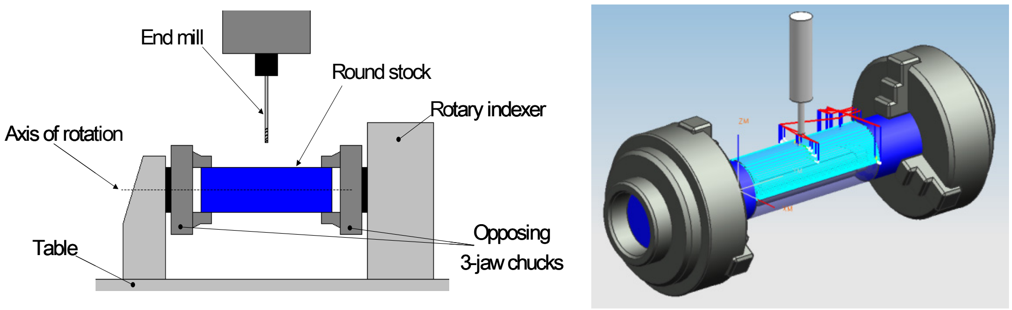


Figure 2.14: Setup for CNC-RP (Wysk 2008)

The main principles of CNC-RP operation can be viewed from three prominent approaches which are based on cutting orientations, toolpath planning and fixturing method. Machining from different orientations around the axis of rotation will assure complete material removal to create the part. In order to determine the orientations, visibility analysis is conducted prior to the development of machining operations. Essentially, this analysis is used to identify visible surfaces of the part when looking downwards along the z-axis which represents the vertical direction of the cutting tool. Several orientations are required since not all surfaces are visible from one orientation. The machining operation is executed within each orientation based on “2½ D” layer-based toolpaths without reference to any features present on the part. The process is almost identical with the layering principle in additive RP except that the toolpaths on each layer indicate the cavity region left after the material is removed. A universal approach is adopted in selecting the cutting tool for machining operations. Figure 2.15 summarizes the toolpath processing steps performed within the CNC-RP method. The size of the parts that can be machined is dependent on the available tool length.

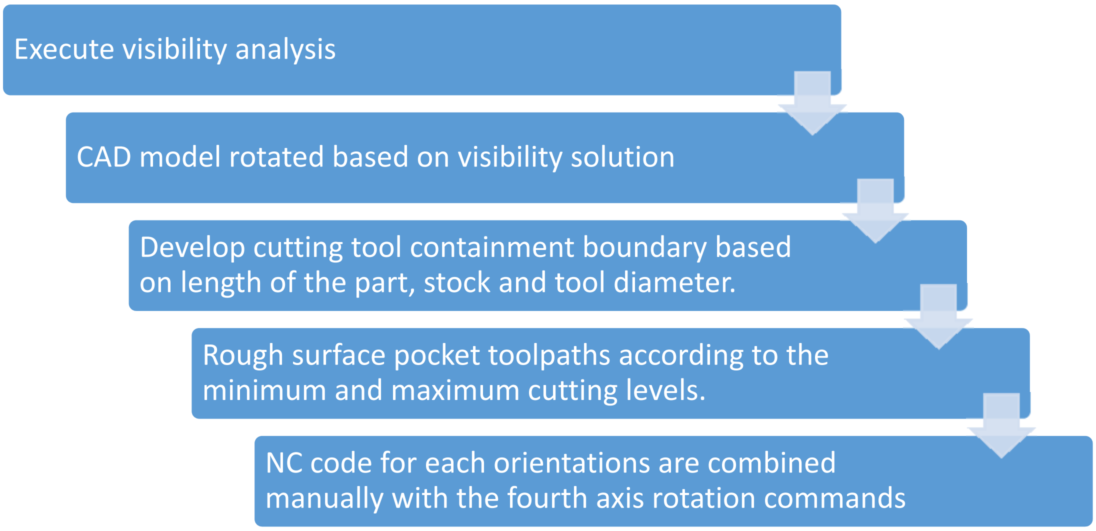


Figure 2.15: Toolpath processing steps in CNC-RP (Frank et al. 2004)

Round cylindrical stock is suitable for use as a workpiece and can be clamped between the indexing devices. Small cylindrical shapes are formed at both ends of the part. These shapes act as a sacrificial supports to hold the part and are machined simultaneously with the part, being removed once the process is complete. The indexing devices used to clamp the workpiece provide a rotational ability that permits machining from various cutting directions. In addition, this unique fixturing method eliminates the complexity of re-setting a datum when re-clamping the part in an ordinary vice. Consequently, it also provides a widely accessible region for the cutting tool to machine the part effectively. The greatest potential of CNC-RP comes from the process planning that has scope for automation and can be executed without any technical expertise. However, the practicality of CNC-RP is limited when dealing with parts that possess severe undercut features and complex shapes.

2.4.2 CNC-RP approaches

2.4.2.1 Cutting orientations

The distinctive approach of using indexing devices in CNC-RP provides fourth axis movement in the system and enables the part to be rotated around one axis into different orientations. During machining, surfaces contained in part geometry are exposed in some of these orientations. Therefore, several orientations are required to guarantee that the parts are machined completely. Now, the challenge comes in determining the values of the orientations and how many of them are needed. These are critically important parameters and need to be determined first before developing the machining operations. In order to handle these tasks, visibility analysis is carried out that is based on line of sight to surfaces and local geometry on the part. The work begins by the preparation of the cross sectional slices of the geometry from the model that initially have been translated into STL format. Each slice contains a set of polygon chains that represent the edges which form the cross-sectional shape of the part. For each polygon chain, there are many segments that are generated from the triangular facets which describe the surface of the STL model. One segment may be visible from different directions and the visibility can be translated in certain ranges. Figure 2.16 presents the terminology of cross sectional slice, polygon chain and segments.

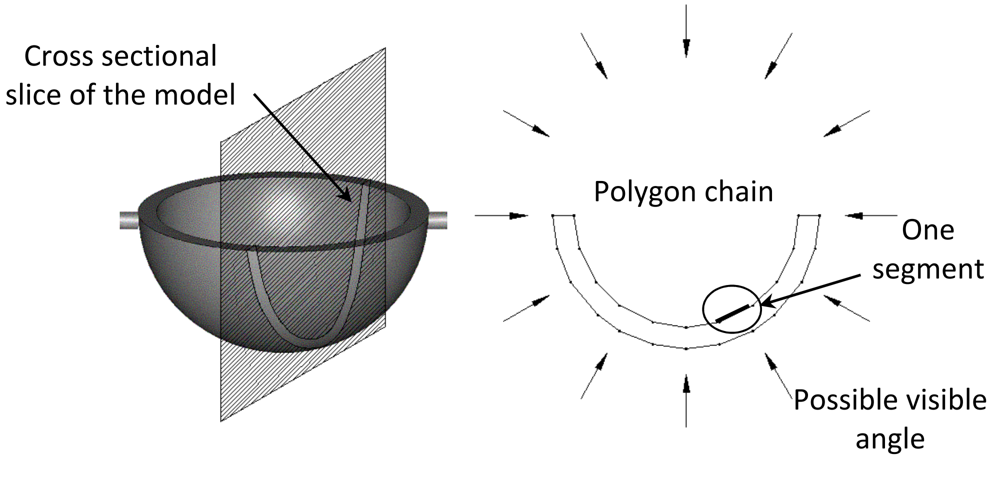
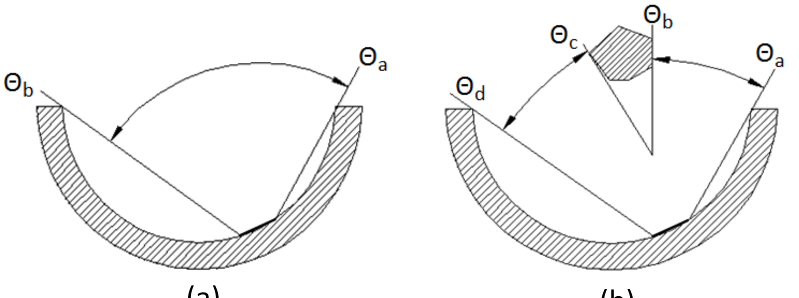


Figure 2.16: Terminology of slice model (Frank 2003)

Once the preparation of the slices file is complete, visibility mapping begins by calculating the polar angle range for each segment in one polygon chain. As illustrated in Figure 2.17 (b), there is the possibility of more than one chain present in each slice and this will cause a blockage in viewing one particular segment (Frank et al. 2004). As a result, the ranges of visibility angles are expanded and become a set of ranges. With this assessment, visibility ranges can be determined for every segment in a polygon chain and can be extended through all the slices that represent one STL model. The analysis continues by deciding on a sufficient number of orientations to machine all surfaces on the part. This is formulated as Minimum Set Cover problem (Frank 2003). Prior to that, similar sets of polar angle ranges that are shared by each segment in all slices are extracted. Modifications are carried out on this data to identify sets of segments visible from each polar angle. The output is used to formulate the set cover problem which proposes a minimum number of orientations that is required to machine the part.



(a) (b)

Figure 2.17: (a) Visibility range for the segment = [Θ_a, Θ_b] and (b) Visibility ranges for multiple chains = [Θ_a, Θ_b], [Θ_c, Θ_d] (Frank et al. 2004)

Searching for the minimum set of index rotations is one of the main objectives in operating the CNC-RP processes. It is predicted that increasing number of orientations will increase the cutting time. Therefore, the solution formulated in the visibility analysis aims to achieve the minimum set objective. Numerous tasks carried out during the analysis are assisted by the visibility algorithms. The software is purposely designed to process the slice files and produce several process parameters as outputs. These include the minimum number of orientations, minimum size of cylindrical stock and the maximum and minimum cutting levels for each orientation (Frank 2003). There are also other criteria that need to be considered while formulating the cutting orientations which include operations sequence, tool length and diameter. Figure 2.18 summarizes the visibility analysis performed to determine a set of cutting orientations.

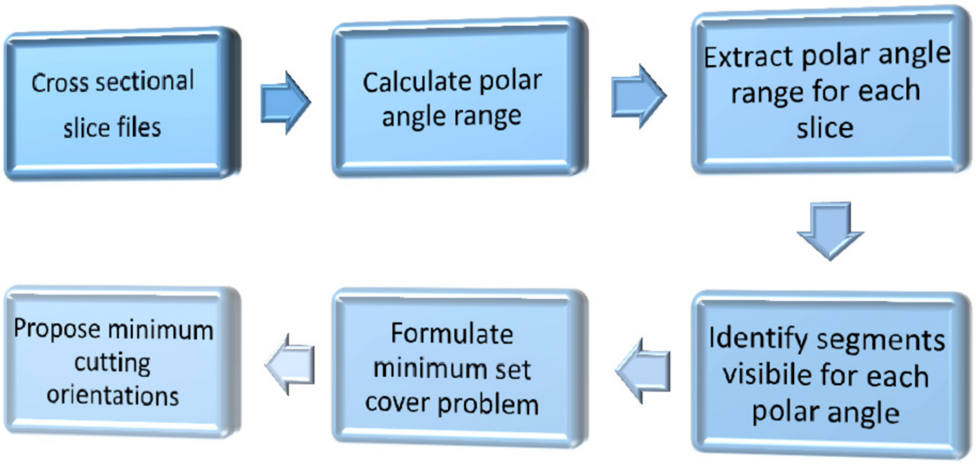


Figure 2.18: Visibility analysis to determine cutting orientations

Machining from several orientations in CNC-RP has proven to be a reliable way to machine parts without re-fixturing the workpiece. Visibility algorithms developed managed to identify the minimum set of orientations required. However, the distribution of the orientations needs to be scrutinized to prevent any potential for thin web formation. Thin webs can be seen as a thin layer of material that forms during the cutting operations due to the process sequence and cutting directions. For example, all surfaces of the part can be machined within two opposite cutting directions. Hence, the first machining operations will remove the material until a predetermined cutting level. Then, the part is rotated by 180^o providing a new orientation for the second machining operation. As cutting proceeds to certain levels, a thin layer of material can develop and may surround the part. Cutting thin material is an undesirable situation in machining because it tends to wrap around cutting tools and hit the workpiece. In the worst circumstances, the penetration process is disrupted and this causes poor surface finish on the part. The best practice is to avoid thin webs by machining the part using at least three cutting orientations. At the same time, the distribution of these orientations must be observed carefully to prevent any tendency of thin web formation. If the set of orientations suggested by the visibility analysis does not obey the thin web requirement, then additional orientations for roughing operations are necessary. Figure 2.19 shows the thin webs formed on a machined part.

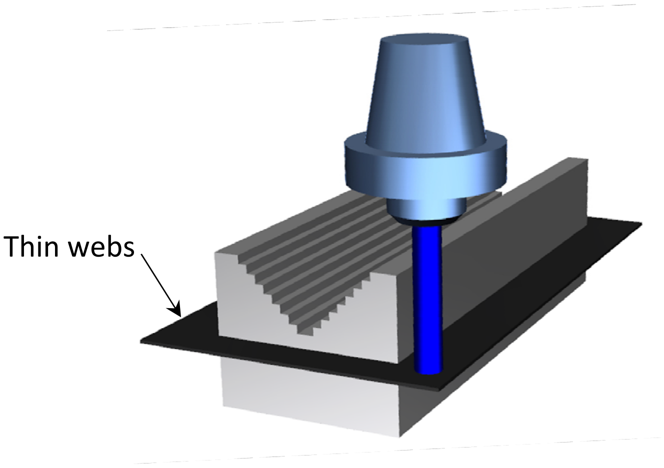


Figure 2.19: Thin webs in formation (Renner 2008)

2.4.2.2 Toolpath planning

CNC-RP executes machining operations without any re-fixturing process between the orientations. Therefore, it is crucial to maintain process continuity as any failure of cutting tools will cause the whole operation to stop. As a consequence, toolpath planning must be developed carefully between the orientations. During machining cutting tools need to reach the last layer of the stock without any collision. At the same time, the part must be completely machined in uniform cutting layers. Basically, the toolpaths in CNC-RP are based on “2½ D” movements where the cutting starts by plunging the tool towards the workpiece and then moving horizontally on x-y axes to shape the part. A flat end mill tool is most likely to be selected as the cross sectional of the part appears in 2D form. In terms of surface attributes, parts produced using this process exhibit the same staircase effect that is present in most AM processes. However, the high capabilities of CNC machines reduce the layer thickness down to 0.02mm or less. Hence, the step appearance can be minimized but a too small layer thickness will increase the machining time.

The feature free approach adopted in the CNC-RP process influences two important decisions in toolpath planning; first, the way machining is executed and second, tool selection. The machining processes have become straightforward as the cutting areas are generalized to cover all surfaces. So, a single operation is required in one orientation to machine the visible surfaces. More importantly, the planning load has been minimized allowing the rapid development of the toolpaths. On the other hand, the cutting tool is selected based on smallest size with sufficient length to reach the furthest visible surface of the part. The tool shank must be equal to or less than the flute diameter to ensure a free collision process. Using a small tool size will guarantee tool accessibility to reach complex surfaces. However, it is admitted this is not a favourable approach as a long tool is susceptible to failure and leads to inefficient machining. Moreover, there is also a tendency to increase the machining time because the small tool requires more passes and thin layer thickness which minimizes the amount of material removed. Nevertheless, these compromises are acceptable to simplify and adopt some level of automation in process planning.

Another important setup in toolpath development is to determine the containment boundary. This setup limits the cutting tool movements within permissible regions while executing the cutting processes. Therefore, it prevents any possibility of collision with other setup apparatus. A general guideline to identify the boundary is by expanding the range of cutting, at least the diameter of the cutting tool for the length and maximum width of the part (Frank 2003). The definition of this boundary is visualized in Figure 2.20.

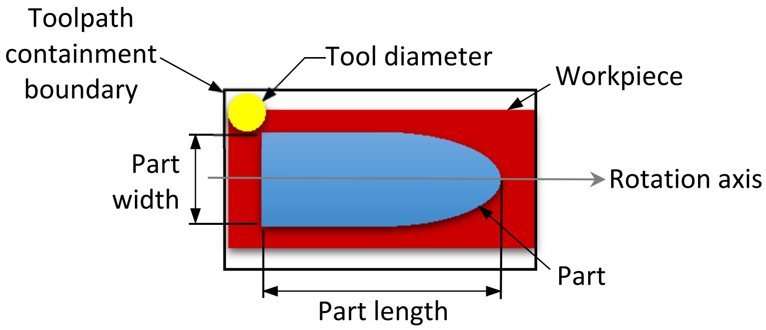


Figure 2.20: The determination of toolpath containment boundary.

To develop the operation sequence, the first cutting orientation is randomly selected from the solution set. Then, the optimization routine is run to identify necessary orientations for next operation sequence. As illustrated in Figure 2.21(a) the first cutting operation is performed based on the orientation selected from the solution set. Depending on tool length, the operation proceeds until the furthest possible level that can be reached by the tool. It is important to ensure that the part does not collide with the tool holder. Then, the second and third operations remove the remaining material and shape the part completely. This process sequence is another way to satisfy the thin web avoidance requirement instead of just machining from a minimum of three orientations.

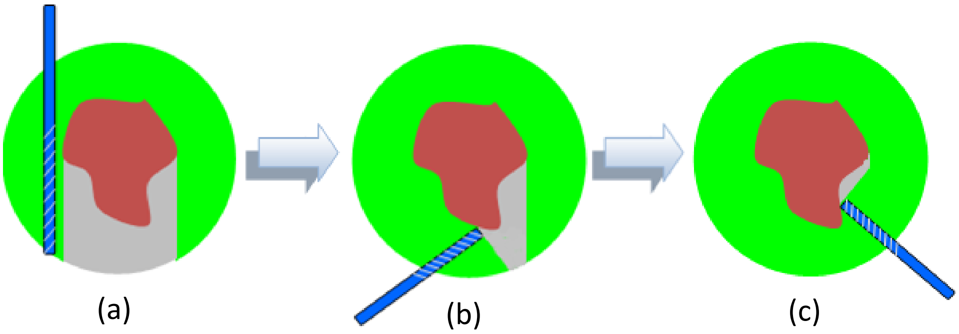


Figure 2.21: Machining sequence in CNC-RP processes (Frank 2007)

2.4.2.3 Fixturing approach

In common machining practice, a vice is widely used as a clamping device to resist forces generated when the cutting tool penetrates the workpiece. This simple clamping method obscures many surfaces especially on the bottom of the part which is in contact with the vice. Consequently, the cutting tool is prevented from machining this region and causes the workpiece to unclamped, re-oriented and re-clamped. This requires technical expertise to setup the workpiece and coordinate system. Any mistakes will lead to coordination errors and defects on the machined part. Because of these problems, CNC-RP needs to adopt a different fixturing approach that is able to fulfil several requirements based on the nature of the operation. First, the fixturing method must maximise the accessible area so that the cutting tool can machine the part with minimum restriction. Second, the approach needs to assist machining in new orientations without re-establishing the coordinate system. And a final important requirement is that the fixture must hold the workpiece rigidly to withstand the cutting forces generated throughout the machining operations.

Considering these requirements, CNC-RP employs a sacrificial support mechanism that is commonly used in AM processes. The aims are to provide sufficient stiffness at the same time increase the tool accessibility on the part (Frank 2007). Unlike AM processes that add material to the part, the supports are created concurrently with the part and remain until machining is complete in all orientations (Frank et al. 2004). Later, the supports are separated from the part through other operations that are considered as post-processes. Prior to toolpath development, the CAD model is modified by adding small cylindrical objects to both ends of the part. These objects serve as sacrificial supports that connect the part to the workpiece. The workpiece is clamped on the indexing devices that provide ultimate support in machining processes. Figure 2.22 illustrates the sacrificial supports employed in CNC-RP.

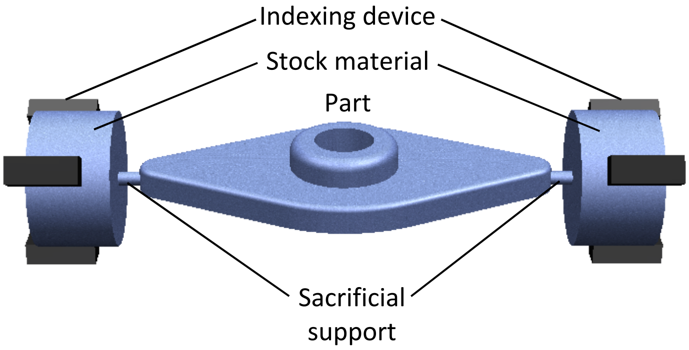
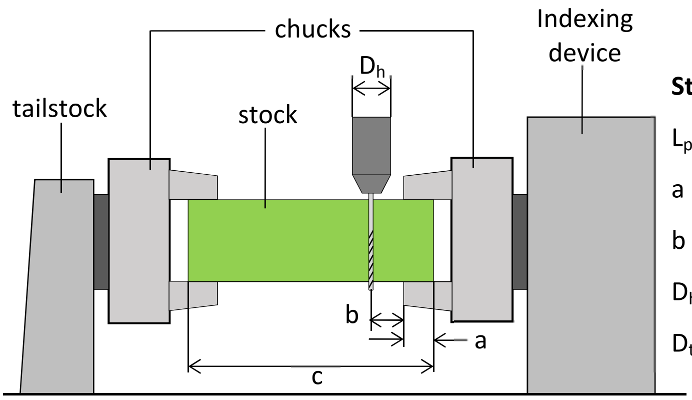


Figure 2.22: Fixturing approach in CNC-RP processes

The mechanism of fixturing in CNC-RP allows the cutting operations to be performed continuously between the orientations without relocating the machining coordinate system. Another concern needs to be addressed in determining the size and number of the supports. Increasing these variables will maximize the rigidity of the workpiece but minimize the tool accessibility. Therefore, it is important to identify an ideal number of supports and their size. Current implementations determine the support size based on a maximum allowable deflection from a simple concentric beam model. Essentially, the support sizes suggested from this analysis are capable of resisting the cutting forces and providing stiffness to the machined part. In addition to this, the length of the workpiece is decided considering the other apparatus that is being setup on the machine table. These include the diameter of tool and the holder, clamping and part length. An appropriate size of workpiece is important for proper clamping, preventing collisions and minimizing material waste. Figure 2.23 illustrates the workpiece setup on the machine table.



Stock length: $c = L_p + 2a + 2b$

L_p = Part length

a = Clamping length

b = Collision offset (x)=$0.5D_h + 0.5D_{tmax}$

D_h = Diameter of tool holder

D_{tmax} = Diameter of largest tool

Figure 2.23: Determining a suitable stock length (Frank 2007)

2.4.3 Developments in CNC-RP processes

The potential of CNC-RP methodology in RM applications has led to several developments in order to strengthen the operations and increase process adaptability. Primarily, these developments can be categorized based on the fundamental approaches discussed on section 2.4.2. There is one development within the cutting orientation and fixturing approaches. However, there are more developments in toolpath planning resulting in several approaches. Most of the solutions attempt to improve the planning phases of CNC-RP which indirectly enhances the machining processes executed later.

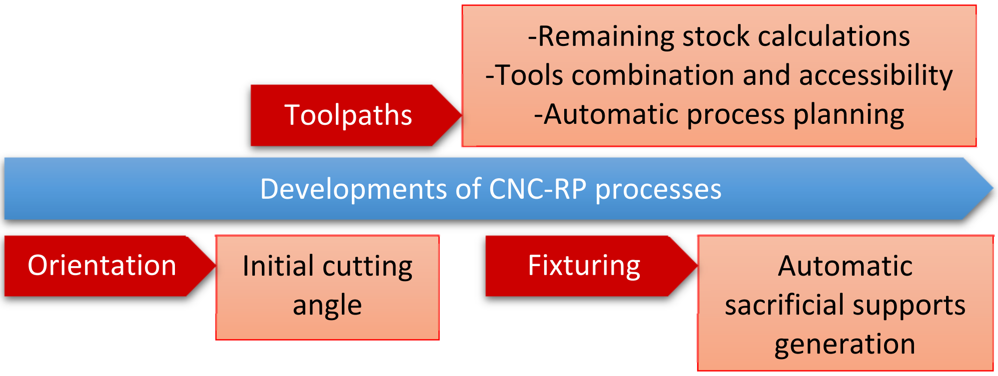


Figure 2.24: Development of CNC-RP processes

2.4.3.1 Improvement in cutting orientations

One of the crucial machining stages in CNC-RP is the process of removing bulk material at an early phase of cutting operations. The effectiveness of visibility analysis in determining the cutting orientation is indisputable. Based on the orientations proposed, the cutting tool can reach all surfaces on the part. However, further assessment is required to examine the set of orientations proposed. The cutting orientations that potentially cause the creation of thin webs have been discussed in Section 2.4.2.1. If the angles output by the analysis could possibly cause thin webs, then, other roughing orientations are used which increases the number of orientations and results in redundant machining.

In order to surmount this problem, an alternative method is suggested while performing the visibility analysis. Using an initial angle input parameter, the set of solutions is expanded and at the same time complies with the thin web avoidance constraint (Renner 2008). The initial angle must be defined based on the angle that covers most of the surfaces on the part. Based on this value, the other two angles are generated with consideration of avoiding thin webs. Then, the set of orientations is assessed to verify the thin web is avoided and at the same time fulfils the finishing operations requirement. Instead of adding to the roughing orientations to prevent thin webs, an alternative way can be implemented by adjusting the solution set with the initial input angle. Consequently, this method also leads to a reduction of machining time.

The implementation can be seen for example in Figure 2.25(b). An initial angle of 270^{o} helps to eliminate redundant cutting orientations and proposes other angles that abide with the requirements to machine the part from multiple orientations. The use of an initial angle manages to improve the set of orientations generated to execute machining operations. Accordingly, the number of cutting orientations can be minimized compared to the solution generated from the visibility analysis. However, other machining requirements such as thin web avoidance and longer tool contact length remain unsolved. Further assessment is still required on the orientations set to avoid the possibility of thin web formation.

In order to minimize the cutting orientations, roughing operations are executed using orientations that are mostly suitable for finishing operations. The assumption that a minimum number of orientations will decrease the machining time has prevented roughing operations from being further improved.

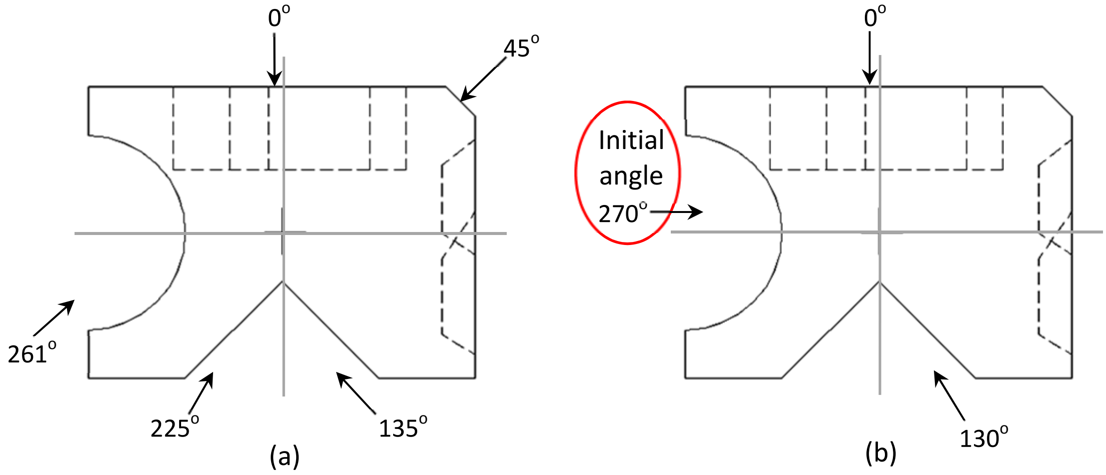


Figure 2.25: (a) Set of orientations proposed by visibility analysis, (b) Solution using initial angle of 270° (Renner 2008)

2.4.3.2 Improvements in toolpath planning

Unlike additive processes, CNC-RP adopts a method of removing material from the cylindrical stock through a set of orientations. As the workpiece rotates to a new orientation, the cutting operations can be inefficient due to redundant cutting of areas that have been previously machined. In order to overcome this problem, a method for remaining stock calculation is invented which consists of three major steps. First, the model is divided into several cross sectional slices and set to give a factor of safety that aims to prevent collision between the tool and the workpiece. Following this, slice approximation and shadowing are performed which are the core operations in this technique. Principally, these operations aim to reconstruct the model by eliminating any inaccessible areas such as small holes and slots. Boolean operations are used to simulate the iterative changes of the stock and assist the toolpath generation by avoiding unreachable cutting areas. Finally, the modified slice data is converted to the STL format through polyhedral reconstruction and can then be processed in a CAD/CAM package (Petrzelka et al. 2010). The significant contribution of this approach is a reduction of toolpath length by up to 65% by avoiding redundant and unnecessary cutting operations. Moreover, the cutting tool remains engaged on the workpiece almost throughout the rough cut operations.

Depending on one size of cutting tool simplifies toolpath planning tasks, but the trade-off for this approach is intolerable as the processing time becomes longer and tends to limit the capabilities of the CNC machine. As a result, the cutting operation is expanded to perform rough and finish cuts using different sizes of cutting tool. Within each orientation, two different toolpaths are constructed. Initially, a roughing operation is performed to remove the bulk of the material from the workpiece. Machining starts from the circumference of the cylindrical stock and is completed once the furthest surface is reached or the stock is completely machined (Frank 2007). Depending on workpiece diameter, the size of roughing tool can be larger and must have an adequate length to execute the operation. Machining at a deep cutting level will increase the tool length contact area. Hence, cutting parameters must be properly controlled to prevent tool failure. After this, the finishing operation removes the remaining material and complies with the quality requirements. Besides, the cutting level is reduced until the centre radius of workpiece. In accordance with the feature free approach, the finishing operation adopts the smallest tool diameter to effectively machine all features present. There are few implications for toolpath planning as both operations employ the same cutting areas. However, the number of operations increases as each orientation contains two cutting operations. Certainly, the combination of different tool sizes for roughing and finishing operations has increased the effectiveness of machining in CNC-RP.

Another method developed to improve the process is by proper combination of cutting tool sizes. Small tools are capable of accessing almost all areas but have a minimum rate of material removal. Conversely, large tools remove more material at faster rates but are not able to access small cutting areas. In order to balance the combination of tool sizes, the Tool Access Volume (TAV) is used to calculate the region accessible for different sizes of cutting tool. Providing the accessible volume calculated using TAV, optimal tool selection and sequencing can be obtained by using another method called Relative Delta Volume Clearance (RDVC) (Lim et al. 2001).

RDVC was developed to relate TAV with material removal rates (MRR) and also between each tool adopted in one set of machining operations. Therefore, an optimum tool size combination for roughing and finishing operations can be determined. Particularly in CNC-RP, these methods can be implemented in a simple way as the method employs a layer-based toolpath strategy. A major task is to determine the volume remaining once roughing operations have been completed as this represents the material left for finishing operations (Renner 2008). Based on the information gained from the TAV and RDVC analysis combined with a set of cutting orientations, minimum total machining time is determined through a Genetic Algorithm technique. Table 2.1 indicates the results produced by implementing the aforementioned methods. Obviously, there is a reduction in total machining time for all three tested parts.

Table 2.1: Comparison results between CNC-RP (Frank et al. 2002) and the proposed approach (Renner 2008)

Test part (a)	CNC-RP Approach	Proposed Approach
Machining orientations (°)	0-45-135-225-261	0-135-261
Roughing tool size (inch)	0.75	0.375
Total machining time (min)	122.542	63.94
Test part (b)		
Machining orientations (°)	0-90-180-225	0-135-180-285
Roughing tool size (inch)	0.75	0.5
Total machining time (min)	53.44	46.97
Test part (c)		
Machining orientations (°)	0-135-180-225	0-45-180-315
Roughing tool size (inch)	0.75	0.5
Total machining time (min)	79.41	67.25

Generally, the developments discussed in the last two paragraphs are concentrated on the tooling approach adopted by CNC-RP processes. Introducing roughing and finishing operations with appropriate cutting tool sizes succeeds in minimizing the total machining time and increases the process efficiency. An optimum combination of tool sizes for roughing and finishing operations is an important aspect in improving the machining operations. However, the integration of cutting tools is only focused on the size rather than the tool geometries. Hence, to achieve good quality parts, flat end mill tools are used with the smallest cutting depths during finishing operations. This could possibly lead to inefficient machining and rough finishing on certain part surfaces. Therefore, a limited selection of tool geometries tends to confine the capabilities of CNC machining in producing high quality parts.

Performing the planning tasks automatically is an ultimate goal that will allow the machining processes to work in a rapid way. Since CNC-RP is built up through integration of various processes, the interaction between CAD/CAM and various algorithms becomes substantial to successfully produce prototypes. Therefore, a customised program has been developed within an available CAD/CAM package that automatically generates NC code for machining (Frank 2007). The program integrates all processing steps involved starting from the CAD model and finishing by producing machining codes. It utilizes the MasterCAM® package as a platform to automate all tasks in process planning. Figure 2.26 presents the processing steps at the planning stage. The first step describes the visibility analysis including the determination of cutting orientations, workpiece diameter and cutting levels. The process continues with the establishment of the coordinate system and the safe working distance between the components in the machine setup. These are part of the requirements to prevent tool collision and maintain process continuity.

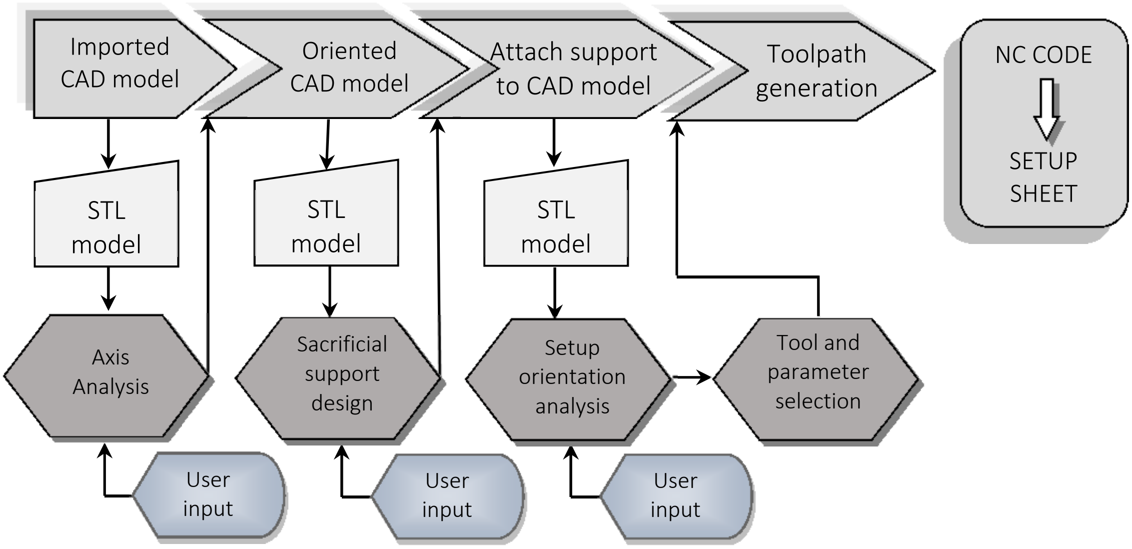


Figure 2.26: Automatic generation of NC code (Frank 2007)

The third step mainly involves the development of sacrificial support features. The outputs from this process are the number, diameter and location of support cylinders that probably become permanent or temporary supports. Finally the toolpath for the operation is developed. Information on tool and cutting parameters are required to execute the task. The STL file translated from the CAD model is mostly used as an input to each processing step. User input is required from the first until the third processing steps. Another development has been recorded that performs similar processes but utilizes a different CAM package called ALPHACAM® (Agrawal et al. 2013). The developed system shared the same objective and aims to automate the process planning tasks virtually and minimizes the dependency on manual controls.

It has been shown that automated process planning can be achieved by integrating commercial CAD/CAM packages with customised programs or algorithms. This can be established as the basis of automation requirements in CNC-RP processes. The main objective is to avoid excessive manual planning that is contrary to the objectives of rapid processing. Considering this, any new approaches that aim to optimise the machining operations must also be equipped with the tools to execute the planning phase. Therefore, customised codes and programming are necessary to perform specific tasks and work as communication tools with the user. On top of that, it must be possible to integrate these codes with commercial CAM software. Fulfilling these requirements will allow cutting operations to be constructed automatically and produce machining codes as the output of the process.

2.4.3.3 Improvement in fixturing method

The sacrificial fixturing in CNC-RP is the support mechanism employed in additive processes. Instead of being used to support overhanging structures, the supports created in CNC-RP work to hold and connect the part with the remaining workpiece. Cutting from different orientations requires the fixture to perform two functions. The first is to hold the workpiece and provide stiffness to the part and the second is to conserve the location information of the part between orientations. These are important requirements to allow continuous machining of the part through the same coordinate system. Recent developments have introduced a method to automate the creation of sacrificial supports in CNC-RP.

Since CNC-RP is developed to cater for a wide range of part geometries, the support structure must be carefully developed. Hence, two types of sacrificial support can be created which are based on permanent and temporary supports. Basically, the permanent support acts as a clamping device that holds the part through the entire machining processes whereas the temporary support is used to strengthen the part but is subsequently removed at the end of the operation (Boonsuk et al. 2009). In attempting to develop an automatic support generation system, a few design parameters need to be considered. These parameters are visualized in Figure 2.27.

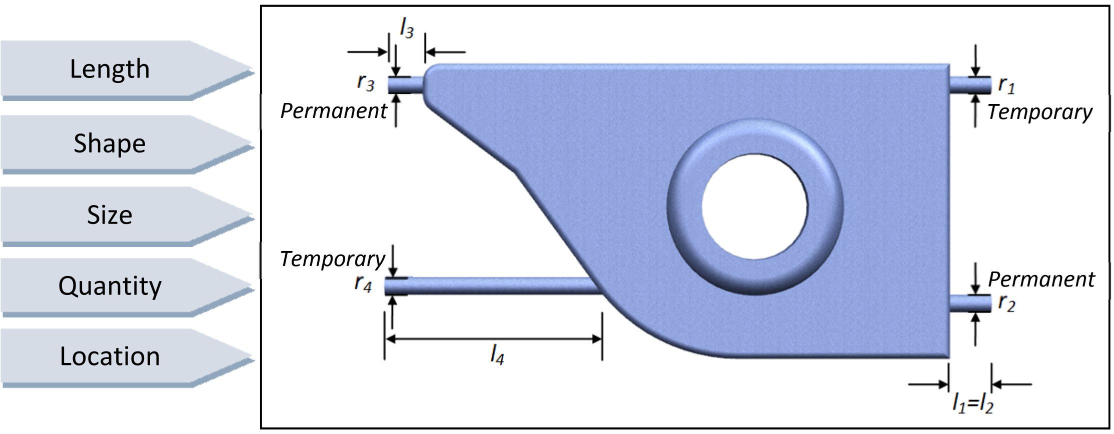


Figure 2.27: Design parameters of sacrificial support consist of length (l_1, l_2, l_3, l_4), shape (cylindrical), size (r_1, r_2, r_3, r_4), quantity (4 supports) and locations (Boonsuk et al. 2009)

There are two forms of deflection that potentially occur in sacrificial supports; bending and torsion. Since the support size is relatively small, the deflections are most likely to happen while cutting forces are being exerted on the part. Therefore, it is important to keep the length of the support at a minimum without restricting cutting tool accessibility. The cylindrical support is a common shape employed because it is easy to locate without considering the orientations and other variables. However, this shape is not suitable for certain part geometries such as thin plates. Several factors need to be considered while determining the support size. These include maximum allowable deflection, part diameter, support length and materials. A pair of permanent supports is a minimum requirement to hold the workpiece. However, if this does not satisfy a maximum allowable deflection value, then additional supports are required. In this development, the locations of the supports are decided with the aim of minimizing the torque effects that are influenced by the distance and cutting force exerted from the centroid of the beam. Ultimately, the automatic design capability is achieved by integrating all these requirements in the MasterCAM® package by using common programming software.

2.4.4 Section summary

This section has discussed the application of CNC machining in RP processes. The methodology developed is known as CNC-RP. Integrating a 3-axis CNC milling machine with indexing devices that provide a fourth axis of rotation, means that the cutting process can be performed continuously in different orientations without renewing the coordinate system. In another words, the part remains clamped even when the orientation is changed during the cutting processes. The core operating principles of CNC-RP can be viewed in three distinct parts. First, the visibility analysis is adopted to assist the determination of cutting orientations. It contains various complex tasks that analyse the visibility of part surfaces in different cutting directions. The second consideration relates to the toolpath planning strategy. In order to simplify process planning, most of the cutting parameters are generalized which slightly affects the machining efficiency. Finally, the introduction of a unique support mechanism has proven an effective work holding method particularly in operations that employ multiple cutting directions. These developments were a breakthrough in the process planning problem that was preventing CNC machining in coping with the automation requirement.

The developments are extended further and have revealed various approaches to strengthen the process methodology. Generally, all the developments shared the same objective focused on automation and process efficiency. The visibility analysis is an effective method to determine cutting orientations. It executes various complex tasks to examine the part geometries. Providing user input to the algorithm manages to improve the set of cutting orientations proposed. On the other hand, several works have been carried out to improve the setup planning and machining operations. These include the implementation of roughing and finishing operations, shortening of toolpath lengths, optimization of tool size combinations and development of automated process planning using commercial CAD/CAM packages. On top of this, the outcomes have benefited the CNC-RP processes in different ways, reducing setup and machining times, minimizing the planning load, improving the efficiency and providing practical solutions to the limitations of previous developments. Indirectly, these improvements also strengthened the establishment of CNC-RP as a reliable RP tool that offers a wide range of applications and distinctive features.

2.5 Critical comparison between CNC machining and AM processes

Both CNC machining and AM processes are technologies that possess unique characteristics in producing prototypes and real parts. Selection between the processes is very crucial as it will influence the achievable quality of the parts produced. Previous sections have identified a number of key issues that distinguish the processes in terms of mechanism and capabilities. Basically, CNC machining is considered as a subtractive process that creates the part based on a series of material removal operations. As depicted by the name, AM processes build the part on the basis of adding material layer by layer until the complete geometry is achieved. The core principles of the methods are totally opposite and therefore each process has its own capabilities and limitations. These can be translated into several criteria. These criteria are highlighted in Table 2.2 that summarizes the differences between AM processes and CNC machining.

Kerbrat et al. (2011) have highlighted two important objectives in modern manufacturing industry which are the improvement of quality and flexibility while minimizing the time and cost of production. Some of the criteria described in Table 2.2 are directly related to these objectives. In order to achieve high quality parts, the accuracy, final properties and raw material are among the factors that are important. Meanwhile, time and cost of production highly depends on process planning, fabrication speed, human intervention and sub-processes. The attractive points of AM processes are most likely to arise from the process planning, automated operation, fixturing approach and geometric design freedom. These distinct features have made AM a suitable process for RP applications.

Table 2.2: Comparison of AM processes and CNC machining (Townsend 2010, Urbanic et al. 2010)

AM	Criteria	CNC machining
Easy to learn, does not require extensive training, involves few variables	Process planning	CAM software challenging to learn, requires extensive training and knowledge, numerous variables involved that are highly coupled
Limited materials	Raw material	Wide variety of metallic and non-metallic materials
Anisotropic material properties, mechanical properties depend on part orientation and build path	Final part properties	Material properties depend on the raw materials used, process can affect the properties, proper control can counteract the effect
Surface finish depends on post processing, difficult to achieve consistency and predictable part accuracy	Accuracy	High level accuracy, Ability to control surface finish through various parameters setup
Depends on part orientation, layer thickness and surface area	Fabrication speed	Depends on cutting speed, toolpaths, depth of cuts etc.
Does not require operator supervision	Human intervention	Requires supervision and intervention
Limited build envelope size	Build envelope	Machines with large build envelopes are available
Not constrained by draft angle, internal geometries, fixture etc.	Geometric design freedom	Complex geometry requires many operations, special tools and fixtures
No special fixturing or tools	Fixturing	Requires fixturing and tools
Post processing which may include removing support material and finishing	Sub-process	Coolant and chips need to be controlled and disposed

On the other hand, CNC machining is better than AM in several respects. This can be seen in the ability to cater for a wide range of materials, guarantee final part properties and high accuracy and surface quality. Indeed, the introduction of the CNC-RP method has strengthened the capabilities of machining processes in terms of fixturing and automated planning. With these capabilities CNC machining can handle full scale part production and can be adapted to rapid processes. Considering recent developments in CNC machining and AM processes, the differences of these technologies can be described based on four vital issues; materials, part geometries, part quality and process planning.

2.5.1 Materials

Most AM technologies are still restricted in processing the materials that are commonly used in part manufacture. In some typical applications, for example in the aerospace industry, AM processes struggle to cope with the requirement of the materials that have to withstand high temperature conditions (Bourell et al. 2009), and it is hard to find materials that have the exact same properties as would normally be used (Todd Grimm 2001). Several AM technologies have been invented to produce metallic parts, but the properties are different from real part properties in terms of strength, variety, homogeneity and proprietary nature (Karunakaran et al. 2012). Therefore, production of final parts that required specific properties is considered as a great weakness in additive processes.

On the other hand, CNC machining is a conventional manufacturing process that is capable of catering for endless types of materials. Development of cutting tools that directly penetrate the workpiece has permitted this process to machine metallic and non-metallic materials. Moreover, some flexibility is conserved while controlling the cutting parameters and this increases the process adaptability to different cutting conditions and material properties. Certainly, this has become a great advantage to the process in creating truly functional parts especially in RM and rapid tooling applications.

2.5.2 Part geometries

The domain factors that define the part attributes in RM are the geometry, accuracy and surface finish as these will portray the level of quality achieved in production. It is undeniable that the key performance of AM originates from the ability to produce nearly any geometric shape from a CAD model (Singh 2010). In addition to this, very intricate shapes including micro parts can be developed due to the nature of the process that is based on an additive mechanism. Fundamentally, AM processes build the part by stacking up the layers of material accordingly. Thus, each of the geometrical features owned by the model can be translated to the part based on a particular layer. At the end of the process, all the interior and exterior features can be formed effectively through the layer build-up operations.

Meanwhile, CNC machining is limited to simple shapes with less geometric complexity (Tut et al. 2010). CNC machining utilizes various types of cutting tools that rotate and move simultaneously on predetermined paths. Fixturing devices are required to hold the workpiece and resist the forces generated from cutting actions. Therefore, any features that contain undercuts and complex shapes need special cutting tools and re-fixturing operations. The native way CNC machining operates causes a limitation in handling complex geometries. However, CNC-RP methodology has revived the process and eliminates the need for re-fixturing while at the same time expanding accessibility to the regions of the part. This method proposes the use of indexing devices to clamp and rotate the workpiece. Then, the sacrificial supports are developed to hold the part and get connected to the workpiece.

2.5.3 Part quality

The presence of the staircase effect is a normal phenomenon with additive processes. Consequently, adverse effects can be seen in the roughness and part accuracy (Wong et al. 2012, Nikam 2005). Most of the AM processes share similar capabilities in terms of achievable accuracy that is limited to around 0.1 to 0.2mm and roughness about 5 to 20µm (Levy et al. 2003, Gu et al. 2012). Over the years, extensive research has been carried out to minimize the staircase effect on part surfaces. (Galantucci et al. 2009, Danjou et al. 2010, Ruan et al. 2010). But, due to the nature of the process, the characteristic is still detectable. In fact, this quality issue limits the widespread use of AM processes in RM and RT applications. Hence, a specific technique is necessary for AM to achieve acceptable surface finish, dimensional accuracy and tolerances (Atzeni et al. 2012).

While AM processes are still struggling to resolve the problem, CNC machines can be considered as an alternative process particularly for manufacturing final and customised parts. CNC machines are capable of controlling the depth of cut to very small values, typically around 0.0127mm, which minimizes the staircase appearance considerably. In machining, surface finish is a prominent factor to be considered in order to ensure the desired final quality of the product (Ramesh et al. 2009). Therefore, a proper control of cutting parameters and tool selection can help to attain good surface finish and accuracy. Because of this capability, CNC machining meets the requirement for producing high specification parts such as tools and dies.

2.5.4 Process planning

Automatic process planning which is similar to touch button operation is one of the attractive features of AM processes. The part is built up based on a native format of the STL model and this simplifies the process planning tasks. Nonetheless, there are still some predefined constraints that need a decision making process which include build orientations, support structure and slicing method (Pande et al. 2008). However, these setup requirements are considered not complicated and can be performed without extensive training. Therefore, AM processes do not rely on specialist or experienced persons to operate and produce the parts. In other words, these technologies are more accessible and not restricted for use in any specific department in industry.

Contrary to this, CNC machining is known as a process that involves numerous tasks and setups during the process planning. In fact, most of the tasks require knowledgeable and experienced persons to develop the machining codes effectively. As a result, the process of transferring the design model into a machined part is considered to take a long while due to the time consuming process planning. This has been a major obstruction for the implementation of CNC machining in a rapid processing environment. Nevertheless, the establishment of CNC-RP with the current advancement of CAD/CAM applications has minimized the dependency on human inputs to develop NC codes. This implies that some level of automation has been embedded in the process planning and this allows CNC machining to be used in RM applications. Constraining several tasks in the process planning has resulted in the simplification of the CNC machining setups. Therefore, the issue of manual process planning no longer restricts the capabilities of CNC machining in RP&M processes.

2.6 Summary

This chapter has described the development of technologies for the application of RP&M. In general, conclusions can be drawn from three important sections of the chapter. Initially, different technologies that work for RP have been discussed. The processes were described by referring to their building mechanism that was based on either additive or subtractive methods. Then, several improvements were highlighted which were still based on the primary methods. These developments were not only restricted to RP but have also been extended to the fields of RM and RT. In order to realize this, overall process capabilities were improved by developing new methods, increasing the ability to work with different kinds of materials and finally aiming to produce high quality parts. The discussion focused on process mechanism, advantages, and limitations. Generally, the discussion in this section is trying to describe the state of the art of RP&M technologies. A key finding that can be drawn from this section is the trend of technology developments for rapid production. AM processes keep struggling to cope with the materials and accuracy limitation despite the process planning and geometric freedom attraction. Theoretically, hybrid technologies seem to be a feasible solution to AM weaknesses but considering the cost and complexity of the systems, the approach needs further revision. Interestingly, the developments in subtractive processes particularly CNC machining have triggered the hidden potentials of this technology for RM processes

The next part addressed the recent technology developed using subtractive processes known as CNC-RP. One of the most challenging tasks in the development of this technology is how to replicate the automatic planning of current AM processes. Therefore, three key principles have been identified to improve CNC machining. As a result, the process methodology was developed based on cutting orientations, toolpath planning and the fixturing approach. Recent research has attempted to strengthen the methodology of CNC-RP. Most of the approaches try to optimise the operations while at the same time employing some level of automation in the process planning. These developments managed to improve the potential of CNC machining for implementation in rapid processing. However, there are some underlying issues that are still not being addressed due to the tight requirement on a universal approach and process simplification. These issues are related to roughing orientations and cutting tools integration. Consequently, some of the benefits of CNC machining are neglected and this leads to process inefficiency. This can be perceived in different aspects such as tool consumption and machining approach. Therefore, further investigations are required and can be focused on improving the machining approach, enhancing tooling and at the same time conserving automation in the planning stage.

The last section of this chapter attempted to provide a clear-cut differentiation between the AM processes and CNC machining. Certainly, these processes can be distinguished based on four aspects that are related to materials, part geometries, quality attributes and process planning. There are some aspects that make CNC machining more capable than the AM processes and vice versa. Previously, AM processes precede CNC machining in planning and part geometries aspects. However, through recent improvements, some level of automation has been successfully adopted in the planning phase. On top of this, an improved fixturing method allows CNC machining to produce more complex parts in one setup and thus bring this process close to a rapid processing nature. Therefore, this process is worth implementing in full scale part production, particularly in RM.

CHAPTER 3

PRELIMINARY STUDIES

3.1 Introduction

Conventional material removal processes such as machining are proven to cater for a wide range of parts and materials. The improvement of machining procedures and process planning has broadened the application of milling machines to RM. Using a 4th axis indexer as a clamping device allows the part to be rotated about one rotation axis. This distinct methodology provides flexibility for tools to remove material from various orientations. However, there are some areas that can be improved in order to enhance the use of milling machines as RM tools. The first improvement focuses on roughing operations by modifying the set of orientations used in machining, and the implications are analysed in terms of machining time and process efficiency. The second improvement considers the integration of tools during finishing operations so that more than one type of tool can be implemented during the cutting process. Generally, these improvements tend to complicate the process planning task but this complexity can be reduced by further developments that assist in keeping planning to a minimum. All of these improvements strengthen the method of adopting milling operations for rapid part production.

3.2 Improvement of roughing operations

Roughing operations are those parts of cutting processes that are particularly concerned with removing a high volume of material and use maximum machine power (Arezoo et al. 2000). Original methods developed by Frank (2007) typically incorporate roughing and finishing operations in one orientation. Within the orientation, roughing operations will be performed first and be followed by finishing operations. Roughing cuts are executed to the greatest depth depending on the selected cutting tool. At least three orientations are used to obey the rule of avoiding thin web formation. Moreover, the orientation is determined based on part visibility analysis that relates to tool accessibility (Frank et al. 2004). Therefore, the orientations proposed are also suitable for finishing operations to achieve final part geometry. These are the general cutting approaches developed from previous studies to establish CNC machine in RM processes. As roughing operations remove the bulk of the material, it is important to improve the process by revising cutting orientations with the objective of reducing machining time. This groundwork analysis is conducted to identify the influence of rough cutting orientations on total machining times in producing identical parts. The objective is to improve roughing operations by increasing the time spent for rough cuts in the overall operation. This will increase the volume of material removed during roughing processes and indirectly reduce total machining time by leaving minimum amounts of material for finishing operations.

3.2.1 Additional orientations for roughing operation

Generally, the method devised suggests additional orientations sets particularly for roughing operations to increase the amount of material removed. The roughing operation can be performed with aggressive cutting parameters as it is not constrained by part quality and accuracy requirements (Sun et al. 2001). This approach is based on adding two opposite orientations that perform roughing operations at the initial stage of the cutting process. Subsequently the process continues by executing roughing and finishing operations contained in visibility orientations. Developing more orientations for rough cuts is a strategy to increase the volume of material removal in roughing operations. Since two opposite orientations are utilized, the rough cuts only proceed to the tangent edge of the sacrificial supports. Thus, remaining uncut material will appear as a thick plate on the centre of the cylindrical workpiece. It will eventually be removed during the roughing operations in the visibility orientations set. Figure 3.1 illustrates the cutting depth to sacrificial support edge from 0° and 180° directions.

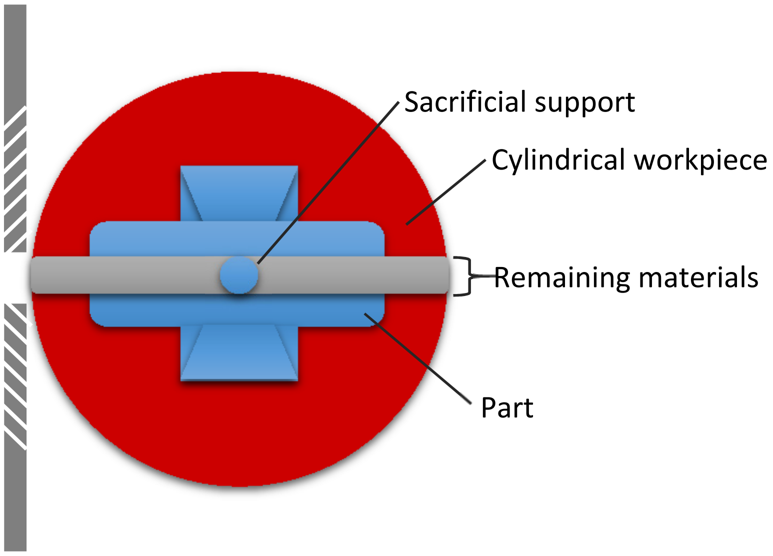


Figure 3.1: Rough cutting depth in additional orientations approach

After completing the two additional roughing operations, all cutting operations in visibility orientations are programmed to cut only to the centre of the cylindrical workpiece. Therefore, rough cuts are not required to cut up to the maximum possible depth. This prevents long tool contact during machining and reduces the force exerted on cutting tools. Searching for optimum additional orientations sets is performed virtually using commercial CAD software and in this study NX7.5 was chosen (Siemens PLM. 2009). For each orientations set proposed, the software will simulate the machining operation and estimate the machining time to complete the process. In order to identify optimum orientations sets, the directions of machining are incremented from 0° to 180° with increments of 10°. The orientations set that indicates minimum machining time is selected to perform the roughing operations. The flowchart in Figure 3.2 summarizes the process flow to find an optimum orientations set of roughing operations.

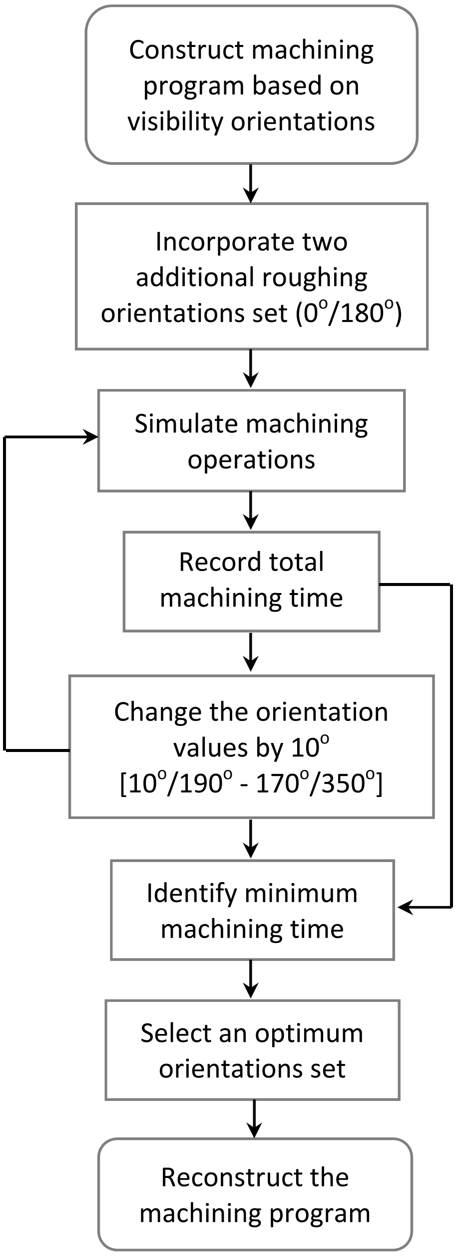


Figure 3.2: Process flow to identify optimum additional orientations

3.2.2 Simulation cutting time

The method that has been developed is applied to the toy jack model as shown in Figure 3.3. This is similar to the model used in a previous study (Frank et al. 2006). Hence, the same cutting orientations can be adopted and this provides equivalent comparison with the approach that will be developed here. Prior to the simulation, the machining program is created using the software. Two standard sets of machining parameters were used which were based on roughing and finishing operations. The additional orientations set are represented as 0° and 180° whereas the visibility orientations are based on 45°, 135°, 225° and 315°. During the simulation stage, the additional orientation value is incremented by 10° and visibility orientations remain the same. Machining time is recorded accordingly while the additional orientation changes to 10°/190°, 20°/200° until 80°/260°. Since the toy jack is considered to be an axis-symmetrical object, the analyses are performed only until 80° is reached.

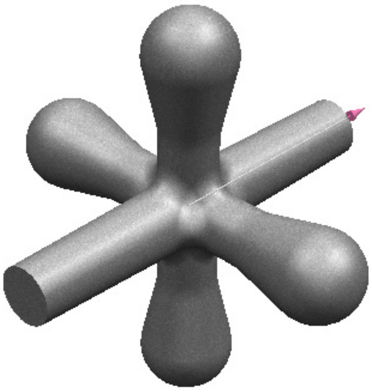
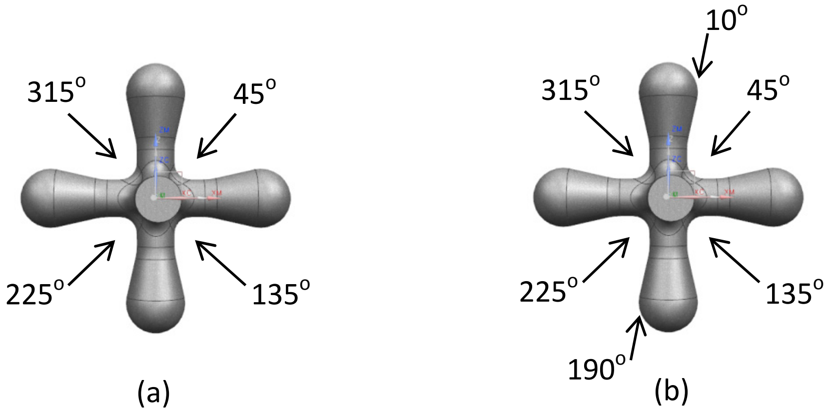


Figure 3.3: Toy jack model (Frank et al. 2006)

A series of simulations are conducted to identify optimum orientations for additional roughing operations. Consequently, the 10°/190° orientations set indicates minimum machining time and is denoted as the optimum orientation set for this part. Based on the result, total machining time is decreased when compared to operations solely dependent on visibility orientations. Machining with these visibility orientations took 9 hours 44 minutes whereas adding two orientations for roughing managed to reduce the cutting time by 28 minutes. The time spent on rough cuts is a contributory factor in this reduction. Visibility orientations executed the roughing operations in about 1 hour and 8 minutes. On the other hand, the method developed spent 1 hour and 27 minutes to rough cut the part. This clearly signifies the influence of roughing operations and orientations on overall machining time. The results obtained are shown in Table 3.1 and Figure 3.4.

Table 3.1: Total machining time recorded on additional orientations set

Orientations set	Total machining time (hour:min)
0^{o} / 180^{o}	09:43
10^{o} / 190^{o}	**09:16**
20^{o} / 200^{o}	09:49
30^{o} / 210^{o}	09:35
40^{o} / 220^{o}	09:25
50^{o} / 230^{o}	09:26
60^{o} / 240^{o}	09:35
70^{o} / 250^{o}	09:44
80^{o} / 260^{o}	09:35



(a) (b)

Figure 3.4: (a) Machining directions employed in visibility orientations and (b) additional orientations (10^{o}/190^{o}) for roughing operations

This study needs to be extended further by exploring other alternative methods that could possibly be adopted. Further analysis could incorporate other parts with different shapes because machining time in this process is highly dependent on part geometries. Moreover, the orientations used can be expanded to cover a wide range of directions. Most of the simulation tasks are performed manually by modifying the orientation values in machining process sequences. Hence, an improvement by fully utilizing the tools available in the CAD software is required. This will be investigated further in the next chapter.

3.3 Integration of tools in finishing operations

Increasing demand from manufacturers has led to RM being viewed as a viable manufacturing method. CNC machining, particularly milling, is widely used in producing discrete parts such as dies and moulds for tooling purposes. Thus, the process can be improved to work as a RM method. The quality of die/mould and machined parts are primarily dependent on surface roughness and part accuracy (Ryu et al. 2006). Therefore, suitable cutting parameters and tool selections need to be prioritized in planning machining operations. Large cutting tools possess outstanding machining efficiency but are restricted in access to small areas, whereas small cutting tools are capable of covering all surfaces but exhibit low cutting efficiency (Lim et al. 2001, Sun et al. 2001). The same kinds of considerations are important when selecting between flat and ball nose end mills. Both possess different capabilities and are suited to different types of surface. Hence, the combination of tool size and type has significant impact on part quality and cutting efficiency.

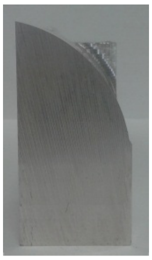
Machining from various orientations reveals different types of surface to the cutting tools. Flat surfaces can become inclined surfaces if the cutting tool is not perpendicular to the surface. The current approach employs the smallest diameter tool with the necessary length to reach the visible surfaces presented on the part. The approach only considers simple “2½ D” toolpaths and consequently flat end mills were chosen for finishing operations (Frank et al. 2004). Currently, there are no clear guidelines to integrate different types of tools in finishing processes. Depending on a single cutting tool is not efficient because of a tendency to increase processing time and consequently increase production cost (Soepardi et al. 2010). Therefore, an explicit method is important to assist tool integration in machining operations and to meet RM requirements.

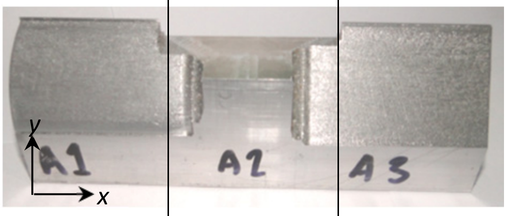
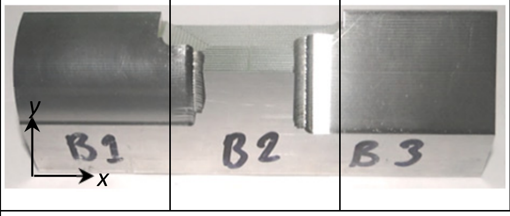
3.3.1 Cutting tools adaptability

An initial study has been conducted to verify the effect of flat and ball nose end mills on surface roughness during finishing operations. Generally, there are three basic classifications of surface that may be present on a part when cutting in different directions. These are freeform surfaces denoted as (1), flat surfaces (2) and inclined surfaces (3). On each surface, roughing and finishing operations are carried out but different types of finishing tools are used. Specimen A utilizes a flat end mill for both roughing and finishing operations whereas specimen B uses a flat end mill for rough cut and a ball nose end mill for the finishing process.

In common with other CNC machining applications, it is feasible to improve surface finish using a single tool by proper control of machining conditions and cutting parameters. However, since this approach adopts an automatic planning task generation, most of the machining parameters remain constant. The reason for this is to keep planning tasks at minimum so that the overall process can be executed rapidly. The spindle speed and feed rates are determined based on tool size, Ø8mm for rough cutting tools and Ø6mm for finishing. The common setup values for finishing operations include 20% tool step over and 0.1mm depth of cut. Table 3.2 summarizes the operations setup for this study.

Table 3.2: Cutting operations and parameters setup

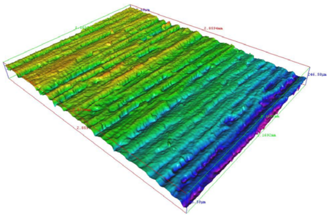
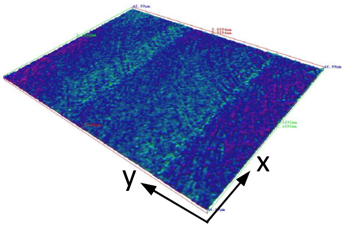
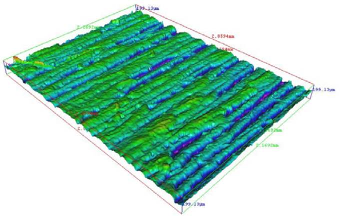
<table>
<tr><th rowspan="2">Tools</th><th colspan="3">Workpiece surfaces</th><th rowspan="2">Side views</th></tr>
<tr><th>Freeform
(1)</th><th>Flat
(2)</th><th>Inclined
(3)</th></tr>
<tr><td rowspan="2">Specimen A
Roughing:
Flat end mill Ø8mm
Finishing:
Flat end mill Ø6mm</td><td>A1</td><td>A2</td><td>A3</td><td rowspan="4">
Left

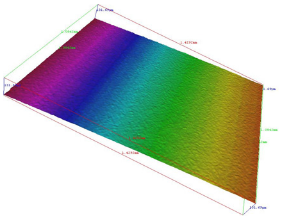
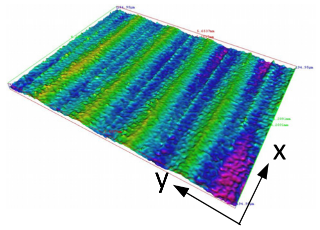
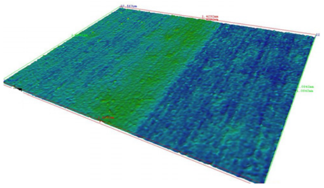
Right</td></tr>
<tr><td colspan="3"> </td></tr>
<tr><td rowspan="2">Specimen B
Roughing:
Flat end mill Ø8mm
Finishing:
Ball nose end mill Ø6mm</td><td>B1</td><td>B2</td><td>B3</td></tr>
<tr><td colspan="3"> </td></tr>
<tr><td>Roughing operations setup</td><td colspan="4">Cut pattern: Follow part
Tool step over: 60%
Depth per cut: 0.8mm
Spindle speed: 2000rpm
Feed rate: 400mmpm
Remaining stock for finishing: 1mm</td></tr>
<tr><td>Finishing operations setup</td><td colspan="4">Cut pattern: Follow part
Tool step over: 20%
Depth per cut: 0.1mm
Spindle speed: 3500rpm
Feed rate: 400mmpm</td></tr>
</table>

3.3.2 Surface roughness

Next, specimens were tested to identify values of surface roughness and the implications of different cutting tools. The roughness parameter used was the arithmetic mean average surface roughness value (R_a) as it is most commonly used in roughness analysis. Measurements were taken using an InfiniteFocus Optical 3D G4f developed by alicona. The scan area ranged from (1.43 x 1.08 mm^2) up to (5.65 x 4.28mm^2). In the analysis, 10x objectives was used, the lateral resolution ranged from 11.74 down to 1.75 µm and the scan speed was around 10µm/s. For freeform and inclined surfaces, measurements were taken based on the direction of cutting depth (y-direction) as it influences surface appearance and quality. However, on a flat surface, both directions (x and y) are tested. Results for specimens A and B are shown in Table 3.3. Times spent to cut each surface are also recorded so that the influences on cutting time can be predicted. The result proves that a ball nose end mill undisputedly has the capability of handling free form and inclined surfaces. Referring to specimen B, the roughness values are 0.67µm for the free from surface and 0.89µm for the inclined surface. It is far less easy to compare roughness values on the same surfaces for specimen A. To the contrary, a flat end mill works perfectly well on flat surfaces and achieved 0.1µm in both x and y directions. The scallop effect caused unacceptable roughness values when using a ball nose end mill on a flat surface. Machining time differences range from about 2 to 10 minutes on freeform and inclined surfaces. Hence, using a ball nose end mill is more likely to extend machining time but it still depends on the overall surfaces present on machined parts.

Table 3.3: Result based on specimen A and B

Specimen A	Roughness(R_a) µm	Machining time (min)
Freeform 	$y = 6.990$	54
Flat  	$x = 0.148$ $y = 0.161$	26
Inclined 	$y = 8.740$	68

Specimen B	Roughness(R_a) µm	Machining time (min)
Freeform 	y = 0.678	64
Flat  	$x = 0.230$ $y = 18.40$	26
Inclined 	y = 0.890	70

The results gathered in this study portray the benefits of using different types of tools at the final stage of machining. Integration of tools during finishing operations is crucial to maintain part quality and accuracy. Therefore, an approach that conserves some flexibility to adopt those tools during the planning phase is developed. The main purpose of this approach is to identify and split the surfaces presented on a part into two categories, flat surfaces and non-flat surfaces. While executing finishing operations, flat surfaces will undergo a designated process flow that utilizes a flat end mill cutter whereas the non-flat surfaces will be machined using a ball nose end mill. This approach is implemented for each orientation which indicates that a tool change may occur depending on the classification of the surfaces. Ultimately, the approach developed must allow some level of automation to be adopted without complicating the process of planning tasks.

3.4 Process planning in CNC machining

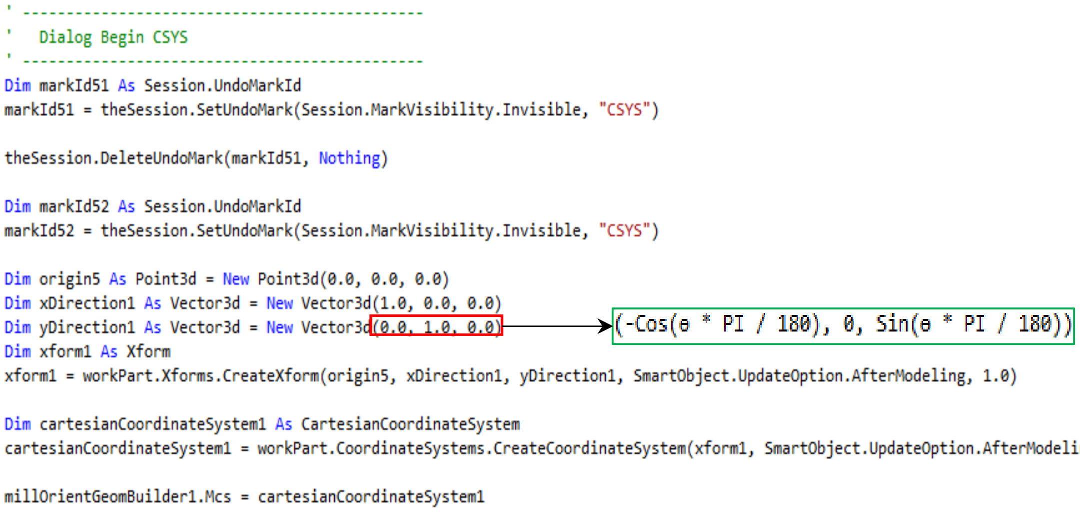
Over the years, automation issues are still unresolved and face difficulty in being fully implemented in many manufacturing fields (Bourell et al. 2009, Bourne et al. 2011). Despite this issue, manufacturers continue to demand highly automated machining processes so that they can remain competitive by producing quality products in minimum time. On the other hand, CNC machining requires extensive work in creating the machining program before the part can be fabricated correctly (Townsend et al. 2012). Tasks such as creating the operations and toolpath planning tend to slow down the process and cause inefficiencies (Liang et al. 1996). However, current developments have produced high technology hardware equipped with various kinds of software. Hence, automation can be absorbed in the process planning tasks using different methods and tools. An automated machining process can be seen to quickly generate correct machining programs without extensive work on trial runs. This is the main principle of implementing CNC machining for RM applications. It aims to automatically generate NC programs and avoid preparation time from exceeding actual machining time.

Recent developments in CAD/CAM systems have stimulated an extensive use of automatically generated toolpaths whilst being less labour-intensive. An adequate automation level in process planning can be achieved by constraining a few process parameters. This approach is adopted in the original study to simplify planning tasks in CNC machining (Frank 2003). For example, the tool selection criteria have been simplified by selecting minimum available sizes and are based on an assumption that the part is feature free. Thus, feature recognition tasks are avoided as small tools are used that are capable of reaching all geometries present on the part. Based on the aforementioned suggested improvements, the planning tasks are rebuilt to integrate those approaches with minimum user interaction. In spite of operating automatically, the programs are expected to conserve some flexibility that will allow the user to setup a few parameters during the planning phase. Having this characteristic will intensify the program's ability to cater for various geometries and features in discrete parts.

Basically, machining from different orientations utilizes the same kind of operation on a repetitive basis throughout the process. This similarity is advantageous as it requires only one type of operation during process planning. However, the parameters used might be different based on roughing and finishing operations. Particularly in this study, programs to assist process planning tasks are developed through the NX software. This system is equipped with programming and customisation tools which act as a foundation for automation in creating machining operations. One of the tools called Journaling is capable of recording and translating commands used in NX to programming languages such as Visual Basic, Java and C++. This function generates a script file that can be run to replay the recorded commands. Moreover, the scripts can be edited to perform specific functions and can be integrated with user interface components. The method is very suited to automating repetitive workflow. Consequently, the Journaling tool is selected as a method to automate the process planning for the proposed approaches in this study. Thus, enormous programming loads can be avoided since all the operations build-up codes are translated into a programming language using this tool. The only task required is the modification and adaptation of the codes to execute specific functions in CNC-RM processes.

3.4.1 Customisation of recorded codes

For this study, a number of commands to build the machining program are recorded using Journaling and are translated to the Visual Basic language. Before any modifications are made, the codes are reviewed to find the main instructions used to control specific parameters. Since the process manipulates many orientation values, a task to create a coordinate system that determines cutting directions is recorded. A portion of the code performing this task is shown in Figure 3.5. In attempts to allow cutting from various directions, the code is generalized by replacing specific commands with variables. In this example, the numeric expression (highlighted by the red box) is generalized with a variable value based on user input described as θ (green box). By providing θ values in the graphical user interface (GUI), the directions of the cutting tool can be changed accordingly based on the input. Following this, the rest of the machining operation can be executed for a particular orientation. The code created by generalising the code from Journaling is known in this thesis as ‘customised code’. The work carried out by the code in Figure 3.5 can be represented as a flow path diagram as in Figure 3.6.



```
' ---------------------------------------------
'   Dialog Begin CSYS
' ---------------------------------------------
Dim markId51 As Session.UndoMarkId
markId51 = theSession.SetUndoMark(Session.MarkVisibility.Invisible, "CSYS")

theSession.DeleteUndoMark(markId51, Nothing)

Dim markId52 As Session.UndoMarkId
markId52 = theSession.SetUndoMark(Session.MarkVisibility.Invisible, "CSYS")

Dim origin5 As Point3d = New Point3d(0.0, 0.0, 0.0)
Dim xDirection1 As Vector3d = New Vector3d(1.0, 0.0, 0.0)
Dim yDirection1 As Vector3d = New Vector3d(0.0, 1.0, 0.0)  →  (-Cos(θ * PI / 180), 0, Sin(θ * PI / 180))
Dim xform1 As Xform
xform1 = workPart.Xforms.CreateXform(origin5, xDirection1, yDirection1, SmartObject.UpdateOption.AfterModeling, 1.0)

Dim cartesianCoordinateSystem1 As CartesianCoordinateSystem
cartesianCoordinateSystem1 = workPart.CoordinateSystems.CreateCoordinateSystem(xform1, SmartObject.UpdateOption.AfterModeling)

millOrientGeomBuilder1.Mcs = cartesianCoordinateSystem1
```

Figure 3.5: Determine cutting direction task in programming language

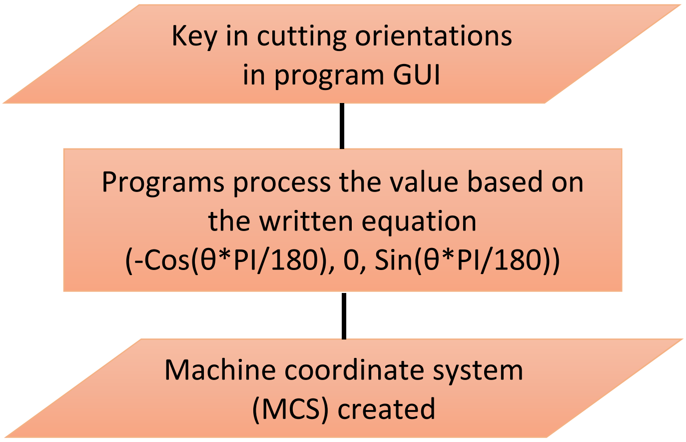
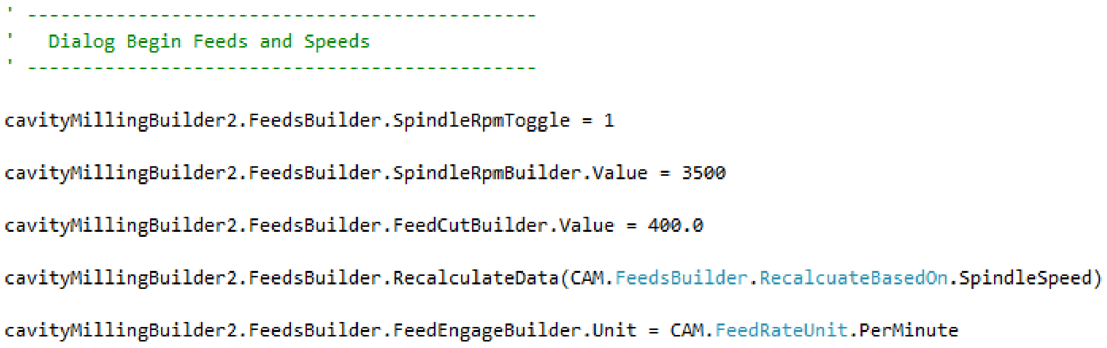


Figure 3.6: Flow path diagram to determine cutting orientations

Another trial is carried out by configuring cutting parameters. Journaling produces codes that clearly contain the values used to setup cutting parameters as shown in Figure 3.7. Therefore, it is quite straightforward to modify the values and make them depend on the cutter size used during machining. The application of Journaling in NX software has shown the practicality of this tool in assisting process planning tasks in CNC-RM. Despite a capability to record and replay various instructions, it effectively translates the tasks to a programming language. Hence, the series of codes produced can be manipulated and modified to perform desired tasks with specific requirements. For this reason, NX is selected as a platform to visualize parts and to construct machining operations particularly for RM processes.



```
' ----------------------------------------------
'   Dialog Begin Feeds and Speeds
' ----------------------------------------------

cavityMillingBuilder2.FeedsBuilder.SpindleRpmToggle = 1

cavityMillingBuilder2.FeedsBuilder.SpindleRpmBuilder.Value = 3500

cavityMillingBuilder2.FeedsBuilder.FeedCutBuilder.Value = 400.0

cavityMillingBuilder2.FeedsBuilder.RecalculateData(CAM.FeedsBuilder.RecalcuateBasedOn.SpindleSpeed)

cavityMillingBuilder2.FeedsBuilder.FeedEngageBuilder.Unit = CAM.FeedRateUnit.PerMinute
```

Figure 3.7: Codes recorded to define cutting parameters

3.5 Summary

This chapter has presented preliminary work carried out to enhance the CNC machining process for RM applications. There are three suggestions proposed which relate to roughing operations, tool selection and process planning automation. In this investigation, the aim was to evaluate the implications of proposed methods on process efficiency and part quality. The additional roughing operations proposed manage to improve process efficiency by decreasing cutting time on the part tested. Additionally it prevents long tool contact with the workpiece that tends to increase the risk of tool breakage. On the other hand, integration of flat and ball nose end mills during finishing operations is worth incorporating in the process. As a part of the process requirement to minimize planning tasks, most of the cutting parameters remain constant. Searching for optimum parameters is not really efficient in this process because it involves diverse variables and part geometries. Thus, the suggestion is made to use different types of cutters for different surfaces presented within a particular orientation. Roughness results show appropriate tools to be used based on part surfaces.

Introducing those suggestions requires planning tasks to be revised and improved. Hence, NX capabilities are fully exploited in assisting the manufacturing tasks. The initial plan proposes the use of computer programming that works within the NX interface to execute planning tasks. A simple modification of the codes has allowed the cutting direction to be determined by the user. The studies conducted have demonstrated acceptable results for the methods to be adopted in the CNC-RM process. However, extensive exploration is required to completely verify the suggested approaches. Further investigations and experimentations are strongly recommended so that machining processes can be recognized as a reliable RM tool. The approaches developed are discussed in detail in the following chapters.

CHAPTER 4

ORIENTATIONS FOR ROUGHING OPERATIONS IN CNC-RM

4.1 Introduction

As part of bulk material removal processes, roughing operations play an important role in machining and shaping parts. During these operations less attention is given to dimensional accuracy and surface quality. Hence, there is some freedom in defining cutting parameters during process planning (Anderberg et al. 2009). Rotating a workpiece on an indexing device on a CNC milling machine preserves some flexibility for tools to cut the workpiece from various orientations. The original approach executed roughing operations based on orientations determined for finishing operations. These sets of orientations are determined by a visibility program that analyses the line of sight towards surfaces presented on the part. Some surfaces are visible in certain orientations dependent on workpiece rotations. An adequate number of orientations will expose all part surfaces so that cutting can be performed effectively. Therefore, the visibility algorithm is developed and implemented to determine the minimum number of orientations. The algorithm analyses the CAD model layer-by-layer to determine a set of segments visible for each angle which later are used to formulate the minimum number of orientations needed to expose all part surfaces (Frank et al. 2006). Subsequently, roughing and finishing operations are performed consecutively for each orientation.

As part of the visibility constraints, there is another rule that needs to be obeyed in determining cutting orientations. Particularly in rough machining, thin webs and strings of material are likely to form if any of the cutting orientations are in opposite directions, for example orientations of 0^{o} and 180^{o} (Renner 2008, Petrzelka et al. 2010). Thin webs are formed at the final stage of cutting during second roughing orientations. A thin string can occur if the roughing toolpath does not widely cover the workpiece area in any particular layer during machining. These are undesirable situations in machining because thin layer materials are likely to wrap around the tool. In the worst circumstances, the tool may break and fail during machining and consequently interrupt the cutting operations. Moreover, it also tends to affect the accuracy as the thin sections possibly distort the part due to the cutting forces generated. It is critically important to maintain process continuity between each orientation and operation. Any disturbance will force the process to stop as all the machining coordinates are disrupted. Figure 4.1 illustrates the formation of thin webs and strings due to machining from various orientations. Currently, a minimum of three machining orientations are implemented to overcome these problems (Renner 2008). Additionally, the distribution of orientation angles must be observed carefully to avoid the presence of any opposite angles in the orientation set.

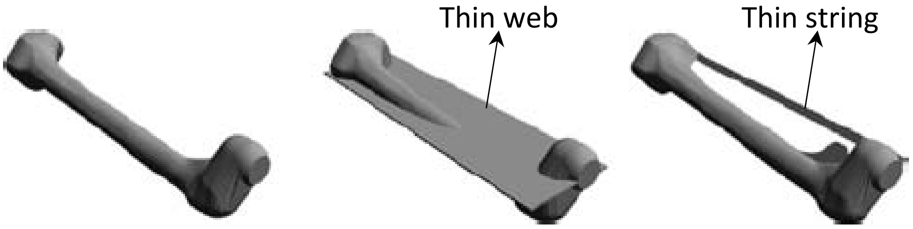


Figure 4.1: Thin web and thin string formation (Petrzelka et al. 2010)

The tool selection in the original approach is based on maximum available length so that cutting can reach the furthest visible surfaces of part (Frank 2007). Roughing operations are executed in two stages. The first stage involves bulk material removal starting from the cylindrical workpiece circumference and finishing at the first visible surface of the part. In the next operation cutting proceeds until the maximum depth that the cutter can reach and is based on workpiece size. Figure 4.2 illustrates the level of cutting employed by this previous approach (Frank 2007). Cutting parameters (speeds and feeds) are determined based on the diameter of tools and the workpiece material. As a common approach in machining, the step down value for roughing operations is usually relatively large to remove as much material as possible. However, since the roughing tool travels to the maximum depth, an appropriate step down value is required related to the force exerted as the contact length increases. This is an undesirable cutting condition because it increases the risk of tool failure and deflection.

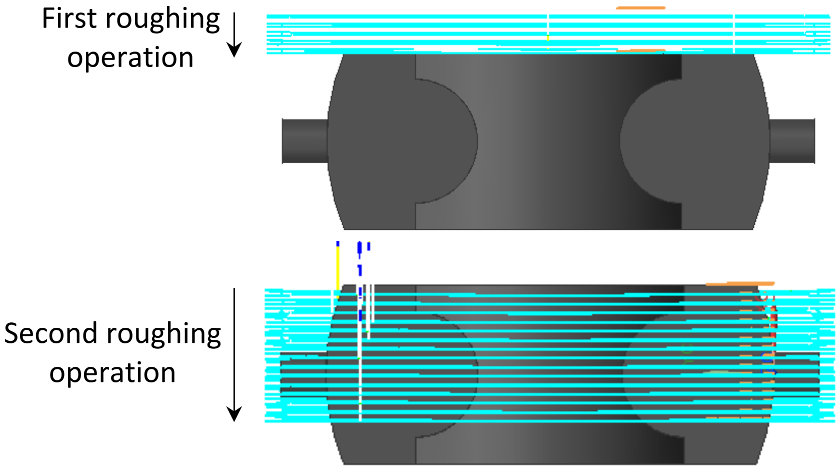


Figure 4.2: First roughing operation (Frank 2007)

Despite the effectiveness of original approaches in dealing with multi-axis machining, they still require further enhancement to improve the process efficiency. It is undeniable that orientations proposed by visibility analysis allow parts to be completely machined. However, roughing operations are constrained to be performed within the orientations used for finishing operations. So far, there has been little discussion on improving orientations for roughing operations. Original approaches tend to keep the number of orientations to a minimum to reduce planning and machining time (Frank et al. 2006). But still this restriction can be disputed because there are several other factors that significantly influence the machining time. In mould and die manufacturing, roughing operations remove massive amounts of material and thus require longer machining times (Hatna et al. 1998). Therefore, this operation needs proper control of cutting parameters and setup to work effectively. On the other hand, at the beginning of the process, the cutting tool is forced to penetrate the material to the furthest possible depth. Although this is an effective method to avoid thin material formation, there will be negative impacts on the tool performance. Longer contact lengths tend to increase the risk of tool failure and deflection. Certainly, any failure will cause the process to stop and the rest of operations to be aborted.

The aim of the study described in this chapter is to evaluate and validate several approaches developed to improve the selection of orientations for roughing operations in CNC-RM processes. As a part of rapid process requirements, time consumed in producing distinct parts is very crucial. Particularly in machining, time spent can be distributed to planning and execution time. Most of the time in planning is spent on the development of machining operations including cutter paths and machining parameters. Meanwhile, execution time depends on workpiece setups, re-fixturing and machining time. Nevertheless, both planning and execution times are strongly correlated as any decision taken on planning will directly influence the machining time. Therefore, minimizing machining time has become a vital concern because of the implications for production cost and process efficiency. Over the years, several works have been published that aim to minimize machining time by optimizing cutting parameters in process planning (Bouzid 2005, Lavernhe et al. 2008, Palanisamy et al. 2007). However, in CNC-RM applications, optimizing cutting parameters will require large numbers of variables to be handled. Hence, it tends to complicate the planning tasks and limits the level of automation that can be adopted in the planning stage. Unlike the previous approaches, the study conducted here intends to optimise the cutting orientations instead of machining parameters. Therefore, orientations sets which indicate less machining time and reliable process efficiency will be chosen as optimum orientations sets for roughing operations.

Basically, this chapter discusses the implications and feasibility of using different sets of orientations for roughing that are independent of finishing orientations. A series of simulations are conducted using several test parts. A methodology is based on two main approaches that consist of several possible methods to optimise roughing operations. The results are assessed in terms of the implications of each method for machining time and process efficiency. Advantages and weaknesses are discussed and at the end of this chapter, a feasible and practical method is suggested. Further enhancements of this method are carried out so that it can be incorporated in the process.

4.2 Methodology

There are two main approaches developed in order to improve roughing operations in CNC-RM processes. Referring to section 3.2.1, a first approach proposes the use of additional orientations (Add-O) at the early stages of machining. Within these orientations, roughing operations are performed and are then followed by the rest of the operations contained in visibility orientations. This approach intends to increase roughing operations performed instead of just relying on operations contained in visibility orientations. Therefore, roughing and finishing operations in the visibility orientations are still being executed during the cutting processes. On the other hand, a second approach is executed by modifying the cutting operations contained in visibility orientations. The roughing operations are extracted and are then assigned to other independent orientations (Ind-O) that are not bound with the visibility orientations. In other words, all rough cuts are executed first using different sets of orientations. Then, the process continues by finish cuts that are based on visibility orientations. A challenge comes in determining which orientation sets work effectively for roughing operations and this will be tackled throughout the analysis.

Original approaches developed by Frank (2007) have constructed the machining operations by incorporating roughing and finishing operations within one orientation. Thus, a first orientation is started with a rough cut followed by a finishing operation. Then, the process moves to a second orientation where the operations sequence is repeated. The orientations set is determined based on part visibility which is mainly effective for finishing operations. The first rough cut requires the tool to cut until the furthest possible surface of the workpiece. The orientations used are also bound by certain requirements such as the avoidance of thin web conditions in order to prevent tool failure. All these aspects create limitations to the process improvement and optimization. Therefore, new methods are explored to enhance the way roughing operations are executed within the overall process.

Experiments were carried out through a series of simulations to evaluate the practicality of both suggested approaches and to discover optimum roughing orientations sets. A number of assumptions have been made while executing the analyses. First, the finishing orientations set is determined based on previous studies by Frank (2003) and Renner (2008). Therefore, the first cutting direction was defined with the objective of covering most of the surfaces on the part. Second, the size of sacrificial support and tools were based on the size of blank used considering the guidelines developed by Boonsuk et al. (2009). This task was carried out using NX 7.5 software via customised coding that simulates machining programs.

The journaling tool in NX was used to record and translate the operation tasks to the programming language. Next, the codes produced were modified using Microsoft Visual Basic 2010. The main intention was to create machining operations based on orientation values given as an input. Since the analyses were performed on a repetitive basis, the codes managed to automate and simplify the simulation tasks. At first, the orientation values with a range of 10^o were used as input. Between each orientation, results are recorded based on machining time comprised of roughing, finishing and non-cutting time. Then, the orientations set that owned the minimum machining time was refined further by changing the values between 1^o and 5^o. For example, if minimum machining time was recorded at an orientation of 20^o then this input value was increased by increments of 1^o to 25^o or decreased by decrements of 1^o to 15^o. The pattern of machining times produced at each orientation was observed and evaluated. Ultimately, the orientation that indicated minimum machining time was denoted as an optimum orientations set. Figure 4.3 summarizes the method adopted to improve roughing operations.

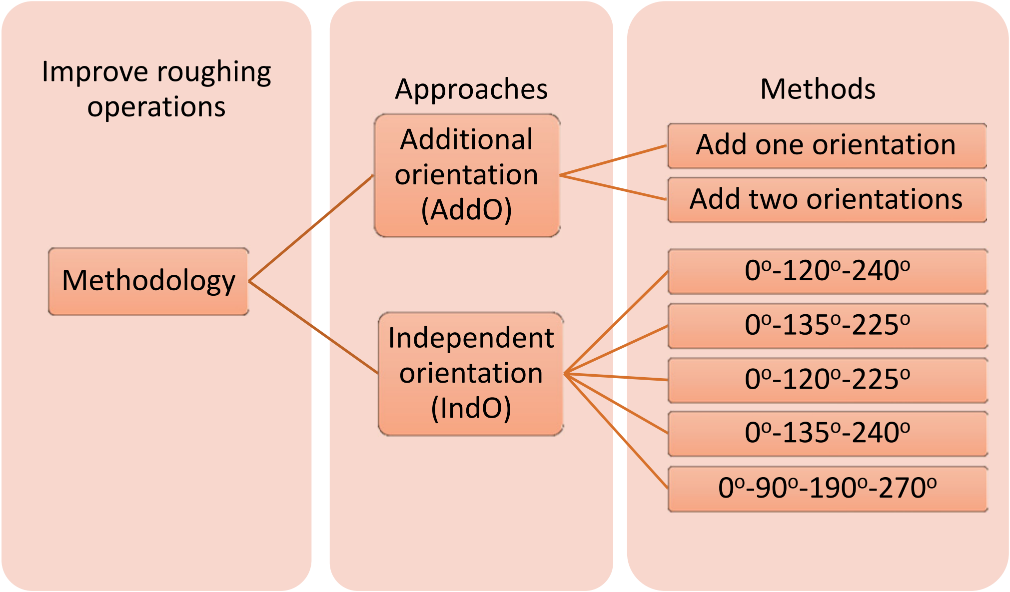


Figure 4.3: Methods derived from approaches used in the study

4.2.1 Additional roughing orientation approach

The Add-O approach involves introducing another machining orientation to the current orientations set. It is divided into two distinct methods. The first method proposes only one additional orientation to perform a roughing operation. Unlike the original approach in determining the cutting depth, the Add-O approach removes material until the centre of cylindrical workpiece is reached. The orientations to be analysed range from 0° to 359°. Figure 4.4 illustrates machining sequences in the original approach compared to the Add-O approach. Orientation A represents additional roughing operations at the first stage of the process sequence.

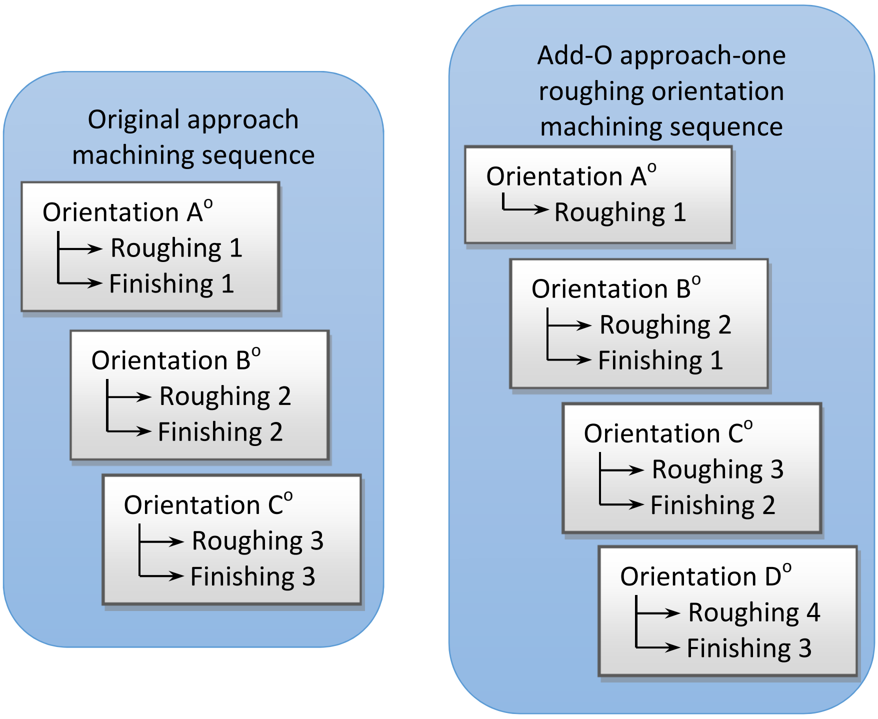


Figure 4.4: Previous and current approach in roughing operations

A second method in the Add-O approach applies two additional orientations and is similar to the method discussed in section 3.2.1. On start-up, the orientations are 0^o and 180^o. During simulation, both orientations are increased gradually at the same incremental value to maintain the opposite direction throughout the analysis (the difference between the two orientations is maintained at 180^o). Figure 4.5 shows the operations adopted in this method. Due to the thin web avoidance requirement, cutting in both directions only proceeds until the circumference of sacrificial support cylinder is reached. The portion of thick material left in the centre of the workpiece will be removed later by other rough cuts in visibility orientations. Principally, the Add-O approach preserves all the operations performed in visibility orientations. The only modification made is the addition of another orientation to carry out the initial roughing operations.

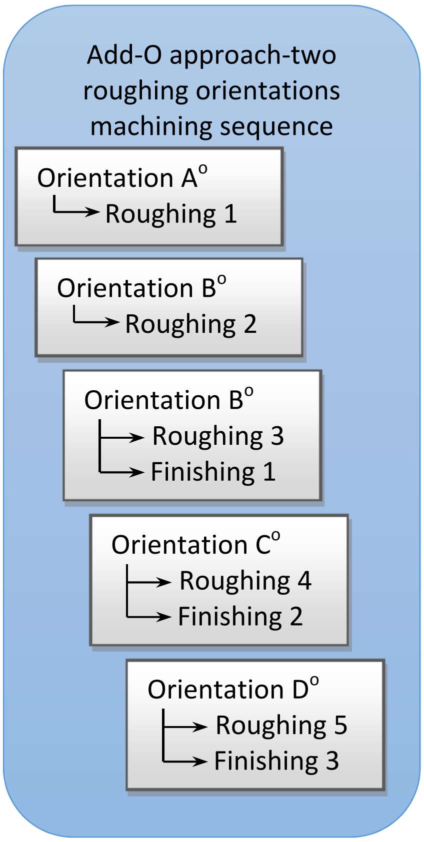


Figure 4.5: Machining sequence for additional two roughing orientations

4.2.2 Independent roughing orientation approach

Instead of adding to the number of orientations, this approach modifies the visibility orientations by taking out roughing operations and incorporating them with other orientations sets. These orientations sets are derived from a combination of cutting directions with which it is possible to cover the complete cylindrical workpiece. Hence, they are built up of between three and four cutting angles that together generate five sets of roughing orientations. Combinations of two and five orientations are not selected due to several issues that were predicted to cause inefficiencies in cutting processes. As a consequence, combinations of these orientations sets are implemented in this study, (0^o, 120^o, 240^o), (0^o, 135^o, 225^o), (0^o, 120^o, 225^o), (0^o, 135^o, 240^o) and (0^o, 90^o, 190^o, 270^o). Figure 4.6 shows the machining steps for three and four orientations sets used in this approach

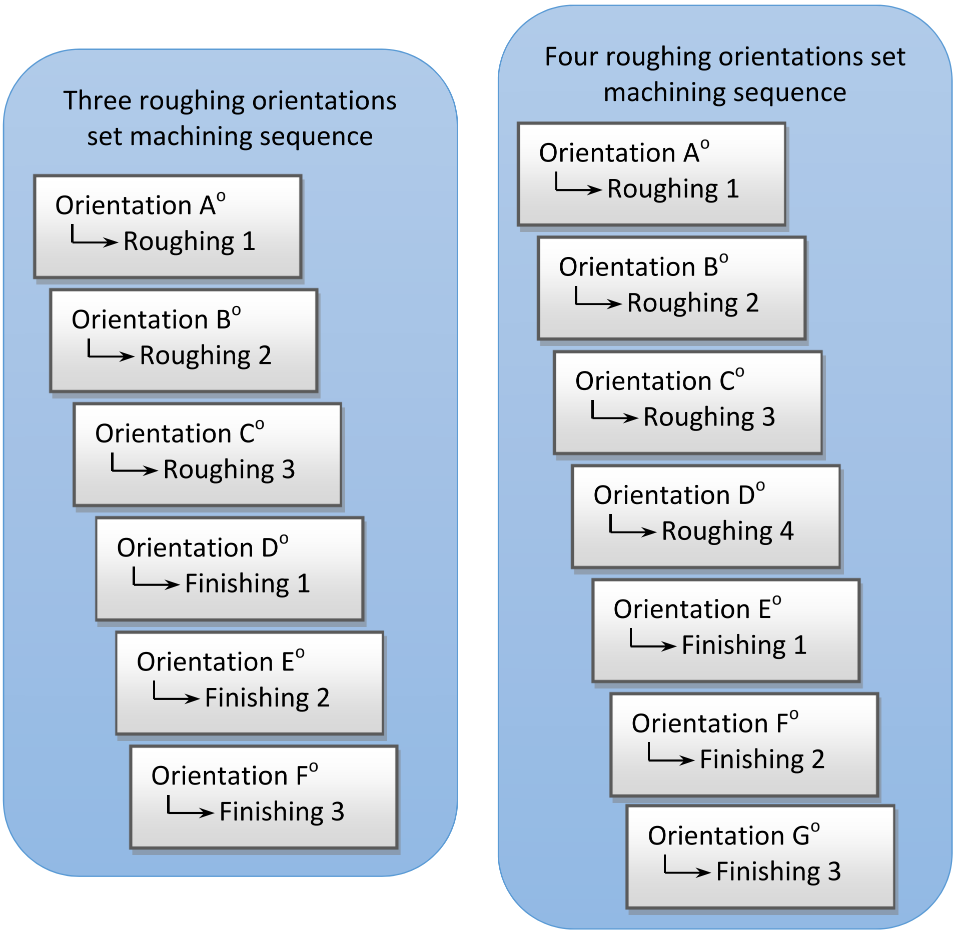


Figure 4.6: Machining sequence for independent orientations approach

In previous studies, cutting from three orientations is a minimum requirement to roughly machine the workpiece without forming any thin material (Frank 2003). Therefore, (0^o, 120^o, 240^o) is the first orientations set used that equally divides the workpiece from one axis of rotation. Next, the second orientations set (0^o, 135^o, 225^o) has been developed based on logical coverage area of a round shape workpiece. Cutting from the 0^o direction is capable of covering the first half of circle whereas the other two directions, 135^o and 225^o, are used to cater for the other half without forming any thin sections. The next two orientations sets are basically derived from the first and second combinations. Two orientation values from each set are swapped to create (0^o, 120^o, 225^o) and (0^o, 135^o, 240^o) combination sets.

Finally, four directions of cutting are derived by equally dividing the 360° contained in one rotation axis. As the number of orientations increase, this combination promises an extra coverage that allows the cutting tool to reach all features present on the part. Initially, the range between each angle is 90° but for the third angle, the value is shifted to 190° instead of 180°. The reason for this increment is because of compliance with the rule for thin web avoidance that may be present during cutting at the third cutting angle. Using this direction, the tool is guided to start machining from an inclined position and cuts the entire workpiece effectively. Based on the derived methods, this approach does not suggest two or five orientations due to several limitations. Machining from two directions is not favourable because it is clear that thin sections will form if orientations are in opposite directions. Shifting one of those will cause inadequate area coverage by roughing operations. Roughing with a five orientations set is inefficient due to many redundant areas of cutting. At the final orientation, there is likely to be no material remaining as it will have been removed at previous orientations.

Based on the methods described, results were obtained by a series of simulation studies using four different models: drive shaft (flange yoke), knob, salt bottle and toy jack. As seen in Figure 4.7, the models consisted of a variety features to form the object. The toy jack model comes from Frank's work (Frank et al. 2002) and is useful for comparison purposes. Multiple features on the part are important criteria to evaluate the effectiveness of the orientations sets proposed. A dimensional sketch for each model is shown in Appendix A. In this study, an objective was to establish a distinct method of identifying a roughing orientations set so that it could accommodate the use of CNC machines for a RM process. The performance of each method has been analysed based on selective criteria which include; (i) minimum total machining time, (ii) maximum roughing time, (iii) minimum finishing time, (iv) minimum non-cutting time and (v) maximum roughing percentage.

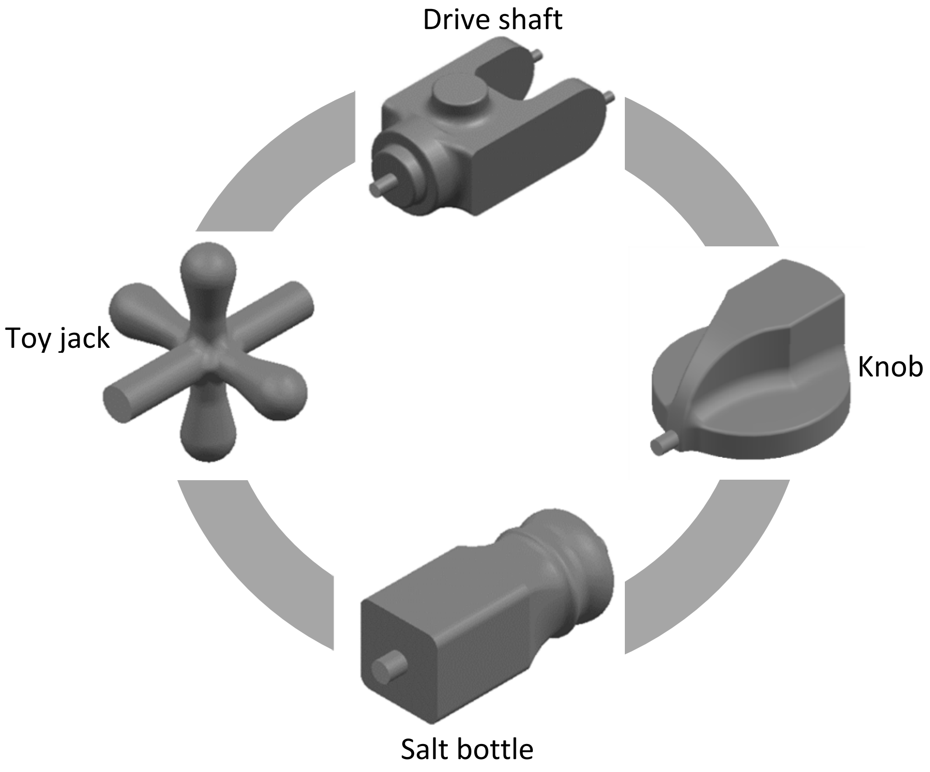


Figure 4.7: Study models

4.2.3 Process planning

The simulation work at the core of this study was carried out using NX7.5 with customised codes to support the generation of machining programs. The main functions of these codes are to modify orientation values and to regenerate the operations. Hence, new cutting times are produced and recorded based on the particular orientation input. There are specific codes developed for each method proposed in this study. Firstly, the machining operations to completely create the parts are developed. Then, a journaling tool is activated to record modifications performed on the operations which primarily involve changing the orientation values. Then, the codes produced are altered to replace an explicit orientation value with a variable. After that, the customised codes are incorporated with a graphical user interface (GUI) developed in the programming software as shown in Figure 4.8. Later, the program can be recalled within the NX interface so that new orientation input can be given to modify existing machining operations.

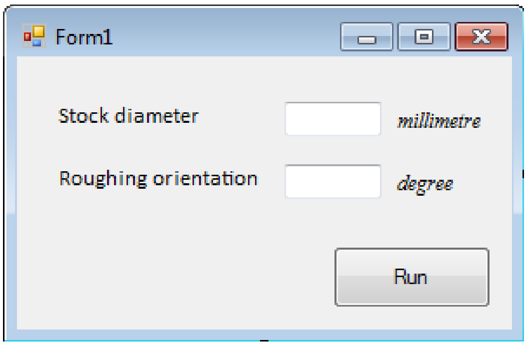


Figure 4.8: GUI for modifying orientation value

Prior to commencing the simulation, process parameters are determined including the type of milling operation used. Since this process employs cutting from several orientations, it is important to ensure knowledge from previous cuts is transferred to the current cutting operation. In the NX Manufacturing application, an In-Process Workpiece (IPW) function was developed to identify material left from prior operations. Thus, the cutting can be assisted to efficiently remove only material remaining from the previous cut. Therefore, the type of operations selected in NX is rest milling because this method has the IPW function and is adaptable to the methods suggested in the Add-O and Ind-O approaches.

Rest milling is a common type of operation in CAM that is specifically used to remove remaining material left from previous operations (Esan et al. 2013). In the NX manufacturing tool, there are several types of milling operations such as cavity milling, plunge milling and face milling, that could possibly be employed and rest milling is included as one of the options. The cutting parameters employed in this process are derived based on dependent and independent variables. To minimize the planning tasks, dependent variables are categorized based on roughing and finishing operations. These variables include workpiece diameter, tool size, depth of cut, spindle speed and step over values. The rest of the cutting parameters remain constant between operations. In addition, the process only used flat end mill tools with a larger tool used for rough cuts and a smaller one for finishing cuts.

The independent variables represent only cutting orientations which are based on user input to the program. Hence, in total seven machining programs that depicted the methods proposed were developed to execute planning tasks. The programs require only one orientation value as an input even though some methods use several orientations to perform machining operations. In order to create the rest of the orientations set, the program increased the input value by adding specific angle values to generate second, third and fourth orientations. A programming code to developed cutting orientation is visualized in Figure 3.5 in the previous chapter. The θ symbol represents the first cutting direction that is based on an input value. Following this, a second orientation is generated by adding a specific angle value to θ. Accordingly, the rest of the codes that are related to cutting orientations are modified in this form. In the end, the modified codes will create roughing operations for each cutting orientation.

During the simulation, a program developed to perform a specific method is run repeatedly based on user input. After the first simulation has been completed, machining time data are taken before the simulation continues with other orientation values. Even though the simulation tasks are not fully automatic, the programs succeed in constructing the machining operations and estimating cutting times. Obviously, implementing customised programs within the NX interface works effectively to create repetitive operations. Moreover, it managed to assist process planning tasks and the building of machining operation sequences. Once a reliable method has been identified, a fully operational program is required to examine machined parts and to propose an optimum orientations set for roughing operations.

4.3 Results and Discussion

The correlation between rough cut orientations and machining time was established. Table 4.1, Table 4.2, Table 4.3 and Table 4.4 summarize the simulation results based on the different models used. The seven columns represent all seven methods proposed including the original approach based on visibility orientations. The rows present machining time data and other machining information. Times are recorded in a (hours:minutes:seconds) format. The roughing percentage is calculated based on the time to rough cut the part compared to the total machining time. Non-cutting time is the time when a tool is moving but not cutting the workpiece, and is due to the predetermined cutting pattern adopted in machining operations. The number of operations is a summation of roughing and finishing operations in the process. There are probably one or two operations contained in one cutting orientation dependent on the methods employed. Information about the optimum orientations set is presented on the last row of each table. It highlights the cutting angles where minimum machining time is achieved.

These tables are quite revealing in several ways. First, they gather all suggested methods including the original approach. Thus, performance between each method can easily being interpreted based on the evaluation criteria. There was significant correlation between machining time and cutting orientation for roughing operations. Both Add-O and Ind-O approaches in some way influence the time consumed for roughing operations which later affects finishing and non-cutting times. Roughing operations effectively remove the bulk of material in the early stages of the process leaving less material for finishing operations. Together, these results provide important insights into the way of roughing operations are executed in machining from several orientations.

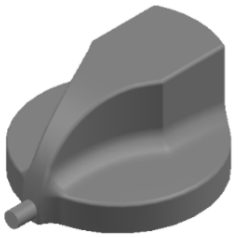
Table 4.1: Drive shaft model

Cutting Parameters	Roughing operations	Finishing operations	
Tool size (mm)	8	4	
Cut pattern	Periphery	Part	
Tool step over (%)	80	30	
Depth per cut (mm)	1.0	0.3	
Spindle speed (rpm)	3000	5000	
Feed rate (mmpm)	500	500	
Remaining stock (mm)	1	0	

Criteria / Approach		Machining time	Finishing time	Non-cutting time	Roughing time	Roughing percentage
		hours:minutes:seconds				
Original	Visibility	04:31:44	03:10:00	00:18:48	01:02:52	23.1%
Add-O	0^o	04:17:39	02:53:05	00:18:39	01:05:58	25.6%
	0^o-180^o	04:31:00	02:46:36	00:18:23	01:26:01	31.7%
Ind-O	0^o-120^o-240^o	04:31:41	03:09:47	00:18:24	01:03:30	23.4%
	0^o-135^o-225^o	04:26:13	03:05:42	00:18:43	01:01:48	23.2%
	0^o-120^o-225^o	04:38:02	03:17:07	00:19:33	01:01:22	22.1%
	0^o-135^o-240^o	05:00:58	03:33:21	00:20:54	01:06:43	22.2%
	0^o-90^o-190^o-270^o	04:13:20	02:38:30	00:16:58	01:17:52	30.7%

Criteria / Approach		Number of operations	Number of tool changes	Optimum orientations sets
Original	Visibility	6	5	32^o-180^o-0^o
Add-O	0^o	7	5	0^o-32^o-180^o-0^o
	0^o-180^o	8	5	91^o-271^o-32^o-180^o-0^o
Ind-O	0^o-120^o-240^o	6	1	15^o-135^o-255^o-32^o-180^o-0^o
	0^o-135^o-225^o	6	1	135^o-270^o-360^o-32^o-180^o-0^o
	0^o-120^o-225^o	6	1	155^o-275^o-20^o-32^o-180^o-0^o
	0^o-135^o-240^o	6	1	80^o-215^o-320^o-32^o-180^o-0^o
	0^o-90^o-190^o-270^o	7	1	90^o-180^o-280^o-0^o-32^o-180^o-0^o

Table 4.2: Knob model

Cutting Parameters	Roughing operations	Finishing operations	
Tool size (mm)	6	3	
Cut pattern	Periphery	Part	
Tool step over (%)	80	30	
Depth per cut (mm)	1.0	0.3	
Spindle speed (rpm)	4000	6000	
Feed rate (mmpm)	500	500	
Remaining stock (mm)	1	0	

Criteria Approach		Machining time	Finishing time	Non-cutting time	Roughing time	Roughing percentage
		hours:minutes:seconds				
Original	Visibility	04:08:36	02:48:54	00:10:43	01:08:59	27.8%
Add-O	0°	04:05:19	02:44:33	00:10:39	01:10:09	28.6%
	0°-180°	04:11:02	02:44:39	00:11:23	01:15:01	29.8%
Ind-O	0°-120°-240°	04:10:47	02:47:08	00:10:10	01:13:29	29.3%
	0°-135°-225°	04:09:46	02:52:13	00:10:06	01:07:27	27.0%
	0°-120°-225°	04:12:25	02:55:07	00:10:44	01:06:34	26.4%
	0°-135°-240°	04:09:40	02:47:24	00:10:38	01:11:38	28.7%
	0°-90°-190°-270°	03:50:09	02:25:54	00:09:11	01:15:04	32.6%

Criteria Approach		Number of operations	Number of tool changes	Optimum orientations sets
Original	Visibility	6	5	180°-45°-315°
Add-O	0°	7	5	165°-180°-45°-315°
	0°-180°	8	5	0°-180°-180°-45°-315°
Ind-O	0°-120°-240°	6	1	0°-120°-240°-180°-45°-315°
	0°-135°-225°	6	1	181°-316°-46°-180°-45°-315°
	0°-120°-225°	6	1	181°-301°-46°-180°-45°-315°
	0°-135°-240°	6	1	0°-135°-240°-180°-45°-315°
	0°-90°-190°-270°	7	1	90°-180°-280°-0°-180°-45°-315°

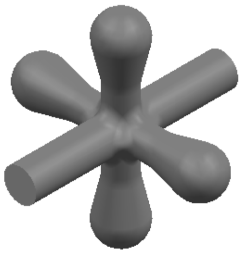
Table 4.3: Salt bottle model

Cutting Parameters	Roughing operations	Finishing operations	
Tool size (mm)	5	3	
Cut pattern	Periphery	Part	
Tool step over (%)	80	30	
Depth per cut (mm)	0.8	0.3	
Spindle speed (rpm)	4500	6000	
Feed rate (mmpm)	500	500	
Remaining stock (mm)	1	0	

Criteria / Approach		Machining time	Finishing time	Non-cutting time	Roughing time	Roughing percentage
		hours:minutes:seconds				
Original	Visibility	04:41:44	02:56:03	00:12:14	01:33:27	33.2%
Add-O	0°	04:31:49	02:46:55	00:12:05	01:32:48	34.1%
	0°-180°	04:35:49	02:45:45	00:12:32	01:37:32	35.4%
Ind-O	0°-120°-240°	04:40:03	03:01:23	00:12:18	01:26:23	30.8%
	0°-135°-225°	04:34:17	02:48:04	00:11:21	01:34:53	34.6%
	0°-120°-225°	04:38:24	02:55:22	00:12:10	01:31:00	32.7%
	0°-135°-240°	04:39:52	02:58:40	00:12:27	01:28:45	31.7%
	0°-90°-190°-270°	04:32:02	02:38:44	00:11:57	01:41:21	37.3%

Criteria / Approach		Number of operations	Number of tool changes	Optimum orientations sets
Original	Visibility	6	5	45°-180°-270°
Add-O	0°	7	5	0°-45°-180°-270°
	0°-180°	8	5	65°-245°-45°-180°-270°
Ind-O	0°-120°-240°	6	1	32°-152°-272°-45°-180°-270°
	0°-135°-225°	6	1	45°-180°-270°-45°-180°-270°
	0°-120°-225°	6	1	44°-164°-269°-45°-180°-270°
	0°-135°-240°	6	1	30°-165°-270°-45°-180°-270°
	0°-90°-190°-270°	7	1	0°-90°-190°-270°-45°-180°-270°

Table 4.4: Toy jack model

Cutting Parameters	Roughing operations	Finishing operations	
Tool size (mm)	8	4	
Cut pattern	Periphery	Part	
Tool step over (%)	80	30	
Depth per cut (mm)	1.0	0.3	
Spindle speed (rpm)	3000	5000	
Feed rate (mmpm)	500	500	
Remaining stock (mm)	1	0	

Criteria / Approach		Machining time	Finishing time	Non-cutting time	Roughing time	Roughing percentage
		hours:minutes:seconds				
Original	Visibility	03:32:56	02:28:35	00:13:56	00:50:25	23.7%
Add-O	0°	03:25:01	02:10:26	00:14:43	00:59:52	29.2%
	0°-180°	03:19:39	02:05:06	00:14:22	01:00:11	30.1%
Ind-O	0°-120°-240°	03:41:33	02:32:50	00:16:18	00:52:25	23.7%
	0°-135°-225°	03:30:31	02:23:33	00:14:35	00:52:23	24.9%
	0°-120°-225°	03:36:16	02:28:49	00:15:21	00:52:05	24.1%
	0°-135°-240°	03:35:32	02:28:01	00:15:26	00:52:04	24.2%
	0°-90°-190°-270°	03:25:22	02:16:04	00:14:06	00:55:12	26.9%

Criteria / Approach		Number of operations	Number of tool changes	Optimum orientations sets
Original	Visibility	8	7	49°-140°-228°-320°
Add-O	0°	9	7	12°-49°-140°-228°-320°
	0°-180°	10	7	35°-215°-49°-140°-228°-320°
Ind-O	0°-120°-240°	7	1	7°-127°-247°-49°-140°-228°-320°
	0°-135°-225°	7	1	4°-139°-229°-49°-140°-228°-320°
	0°-120°-225°	7	1	6°-126°-231°-49°-140°-228°-320°
	0°-135°-240°	7	1	6°-141°-246°-49°-140°-228°-320°
	0°-90°-190°-270°	8	1	50°-140°-240°-320°-49°-140°-228°-320°

It was hypothesized that improving the roughing operations would minimize machining time and enhance process capabilities. The results of this study reveal possible methods to be adopted in determining roughing orientations sets. These findings further support the idea of using different orientations sets to execute roughing operations that are not bound with visibility orientations (Renner 2008). Referring to the results, the effectiveness of each method in performing roughing operations is evaluated. In addition to timing criteria, the methods are also assessed in terms of process planning and adaptability with various part geometries. Table 4.5 summarizes the overall results based on selective criteria. It can be seen that roughing through four orientations sets fulfils the assessment requirements and was the most favourable method among the tested models. Some of the models shared very similar time values and thus caused two methods to be recorded under one criterion. The presence of other methods requires extensive analysis to identify reliable and effective roughing methods.

Table 4.5: Summarized results based on evaluation criteria

Model Criteria	Drive shaft	Knob	Salt bottle	Toy jack
Minimum machining time	4 orientations	4 orientations	1 orientation/ 4 orientations	2 orientations
Maximum roughing time	2 orientations	2 orientations/ 4 orientations	4 orientations	2 orientations
Minimum finishing time	4 orientations	4 orientations	4 orientations	2 orientations
Minimum non-cutting time	4 orientations	4 orientations	3 orientations/ 4 orientations	Visibility orientations
Maximum roughing percentage	2 orientations	4 orientations	4 orientations	2 orientations

4.3.1 Implications of additional roughing orientations approach

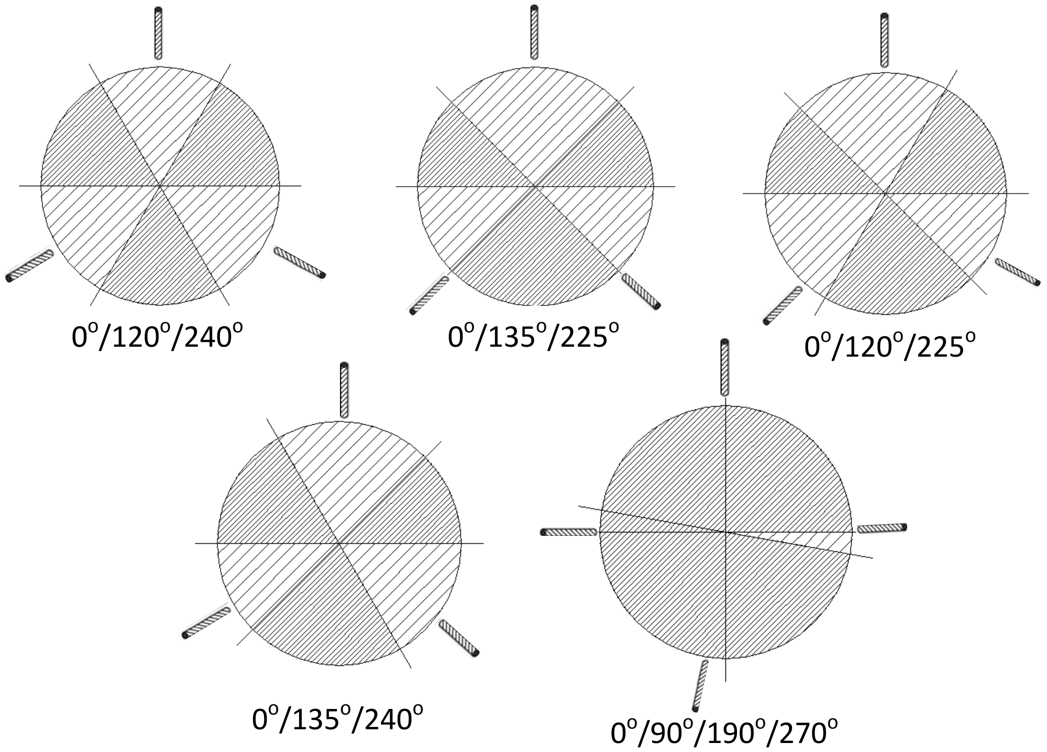
The approach that increases the number of rough cuts in existing machining operations managed to minimize machining time in some of the study models. The increasing of rough machining time influences the finishing operations and finally reduced overall time required to machine the parts. For example, the results from the toy jack study indicate an increase in roughing time of about 10 minutes in the

Add-O two orientations method. Later, finishing time is reduced as is the total machining time. However, in some isolated cases as indicated in the drive shaft model, cutting time does not remarkably reduce even when roughing time shows an increased value. This is probably because the increment was not sufficient to reduce the finishing time required by the operations. Besides, a diversity of geometric features owned by the models may contribute to this machining time pattern.

To the contrary, the Add-O approach tends to increase the number of machining operations adding to the existing operations contained in visibility orientations. Thus, the practicality of the approach can be argued as it adds other roughing operations at the same time as it keeps roughing operations in finishing orientations. To a certain extent, there will be no material to be machined as it will have already been removed by earlier roughing operations. Furthermore, additional orientations selected must consider current orientations used in the visibility approach. Any redundant angles will cause inefficiency due to the repetitive work and an increase in the tendency of thin section formation. Eventually, this situation causes the approach to fail the thin web avoidance requirement in machining from various orientations. Meanwhile, from a process planning perspective, the additional roughing orientations require simulation to proceed on a certain range of orientations. One roughing orientation needs 360^o simulations while analysis from 0^o to 179^o is sufficient for the two orientations method. This is due to the combination of opposite cutting directions that cover all possible orientations.

4.3.2 Implications of independent roughing orientations approach.

Splitting roughing operations in current visibility orientations seems to be a feasible method to improve roughing operations. It allows roughing tasks to be carried out independently without any reference to the orientations for finishing operations. Unexpectedly, the number of tool changes also reduces and occurred only once throughout the machining operation. Once all rough cuts have been completed, the cutting tool is changed to a smaller size to cater for finishing operations. Although the CNC machine is equipped with an automatic tool changing system, it is a good practice to keep changes to a minimum and avoid any interruption to the machine coordinate system. In accordance with the present results, several methods that utilize three and four orientations are employed to perform roughing operations. These orientations sets are derived from sensible cutting coverage towards a cylindrical workpiece. The coverage areas of these orientations sets are visualized in Figure 4.9. Heavy crosshatch sections represent the area where cutting tools can reach the workpiece from more than one direction.



$0^o/120^o/240^o$ $0^o/135^o/225^o$ $0^o/120^o/225^o$

$0^o/135^o/240^o$ $0^o/90^o/190^o/270^o$

Figure 4.9: Independent roughing orientations sets coverage area

In general, machining simulation through three roughing orientations does not generate a significant result. The relative performance of this method is closely dependent on part geometries. Comparison between each method under this category indicates the combination of 0^o-135^o-225^o shows a minimum machining time for all the simulation models. But, a notable weakness is identified when dealing with a complicated part that has a restricted region for tool accessibility. It results in some regions not being covered leaving large amounts of material for finishing operations. This can be seen on the drive shaft model as illustrated in

Figure 4.10 where the tool had limited access to remove a small portion of material after completing all three roughing orientations. Process planning wise, an orientations set such as 0^{o}-120^{o}-240^{o} is capable of minimizing the simulation loads where analyses are executed only until 120^{o}. However, this is not applicable to other orientations sets as the orientations are not equally divided.

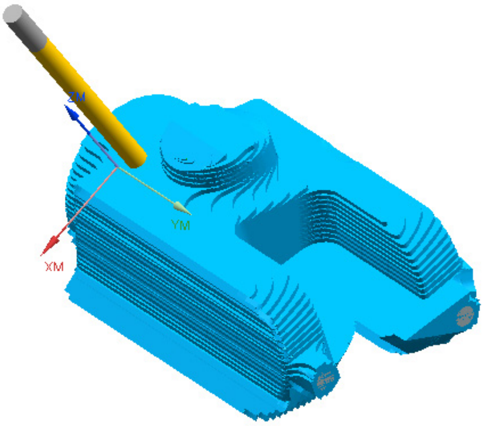


Figure 4.10: Remaining material left in three roughing orientations

Apparently, an attempt to use four orientations seems to be a viable solution in optimizing roughing operations. Referring to Figure 4.9, it is clearly seen that roughing through four orientations indicates the highest coverage of overlapping regions. Besides this, the bulk volume of material is effectively removed leaving a reasonable amount for finishing. Hence, this method may be applicable for executing roughing operations efficiently. Furthermore, this study also signifies that this approach managed to minimize total machining time by spending more time on rough cuts. According to the results produced, roughing through four orientations satisfies most of the evaluation criteria. Some criteria suggest other methods but further analysis exposes the weaknesses that may be present during implementation. For example, two additional orientations caused repetitive and inefficient roughing processes. Meanwhile, independent three roughing orientations faced difficulty in accessing certain part geometries.

Unlike the previous approach, rough cuts using four orientations minimize the cutting depth as the roughing tool is only required to cut until the centre of cylindrical workpiece. This is a practical approach to prevent the tool from cutting at the furthest depth which tends to increase the possibility of breakage. Considering all these capabilities, four independent orientations can be denoted as an improved method for roughing operations in CNC-RM processes. However, since the orientations are not equally distributed, simulation work may sometimes depend on part geometries. Axis-symmetrical parts would probably minimize the range of orientations to be analysed. One of the issues to emerge from this approach is the increased number of orientations compared to other methods. But, the effect on planning tasks can be compromised by using a customised programming tool as implemented in this study.

Another precaution that should be addressed is the sacrificial support size. During the roughing process, the cutting tool will also remove and shape the sacrificial support that connects the workpiece and the part. Once roughing operations have been completed, there is only small diameter of support left to resist cutting forces generated during finishing operations. An inadequate diameter will cause the support to fail during finishing operations and disrupt the fixturing method. The previous study had already suggested an ideal support diameter based on the size of the workpiece, material and allowable maximum deflection (Boonsuk et al. 2009). Therefore, this method is still applicable in this approach as it can withstand the cutting force generated throughout the process. Further work is required to establish this method completely and care should be taken in improving the simulation tasks.

4.4 Summary

The study has investigated the implications of using different orientation sets, particularly for roughing operations. The main goal was to discover a feasible method that can improve roughing operations and the whole process efficiency. In contrast to the original approach that pooled roughing and finishing operations under one orientation, this work introduced a new method that performed roughing operations on an independent orientations set. The evidence from this study suggests that roughing through a set of four independent orientations managed to minimize total machining time and at the same time increased the process efficiency in terms of cutting tool usage. The findings from this study make several contributions to the use of CNC machining for RM applications. First, it proposes a distinct method to improve orientations for roughing operations. This leads to the increasing of rough cutting time which causes a reduction in the total machining time. Hence, it minimizes production time and makes the process work more rapidly.

Other benefits can be seen in terms of cutting approach where the present method limits cutting depth to the centre of the workpiece only. Thus, any possibility of tool breakage is substantially reduced as it is not used to cut to the maximum possible depth. The current investigation was limited by the range of orientations used to search for an optimum orientations set. A customised program employed to assist planning tasks still requires orientations to be input by the user and times are recorded manually. Therefore, certain ranges of orientations are used to find minimum machining times and do not cover all possible cutting directions. The next development emphasizes the planning task in searching for and identifying a four roughing orientations set that effectively fabricates parts with the shortest time.

CHAPTER 5

MUTIPLE TOOLS FOR FINISHING OPERATIONS IN CNC-RM

5.1 Introduction

In manufacturing engineering, performance of the machined parts and production costs depend highly on the quality of surface finish (Davim 2001). Therefore, improving surface finish has become of major interest, especially in the field of RM. Recent developments in operating CNC machining for rapid processes have led to the improvement of part quality. Unlike other RM processes, CNC machining is capable of cutting at a very shallow depth and thus manages to minimize the layered appearance on the part surface. This is a key factor that encourages the implementation of CNC machining to rapidly produce identical parts. Basically, machining operations including rough and finish cuts are distributed to several orientations determined by visibility analysis. During finishing operations, the cutting tool is controlled to reach all visible areas of the part from one particular direction. Prior to this operation rough cutting is performed within the same orientation.

Previously, a general approach has been adopted in the selection of cutting tools to perform finishing operations. In order to simplify the process planning, feature recognition tasks have been avoided. This earlier approach recommends the smallest diameter tool to finish cut the part (Frank et al. 2004). Therefore, a flat end mill tool is most likely to be selected as the process analyses parts based on 2D cross-sectional layers of part geometries. Moreover, using a single tool with the smallest diameter for finishing operations removes complexities during process planning. Between each orientation, the cutting tool is programmed to machine all the visible areas. Thus, similar cutting regions can be easily defined and this simplifies the development of cutting toolpaths. Hence, the general tool selection approach is expected to permit tool accessibility for most of the shapes presented and finish cuts the part effectively.

However, relying on a single tool during finishing operations tends to limit the capabilities of the CNC machine in producing high quality surfaces on the part. One of the disadvantages is a noticeable staircase effect that can be seen especially on the contour surfaces of the part once machining has been completed. Although cutting occurs with small depths of cut, the effect still appears due to the flat end mill geometry (Frank et al. 2002). Furthermore, a small cutting depth will result in longer machining time and leads to inefficiency in the process. The problem is intensified further when examining tool accessibility. Machinability analysis that has been developed reveals that some regions may not be accessible to the flat end mill tool to remove the material (Li et al. 2006). This will affect the dimensional accuracy of the part produced as it does not follow the predetermined size and shape of the model. Figure 5.1 illustrates non-machined regions on a toy jack model. It is possible to overcome these problems by introducing different cutter geometries. So far, however, no clear method has been developed to integrate different tool types for finishing operations in CNC-RM processes.

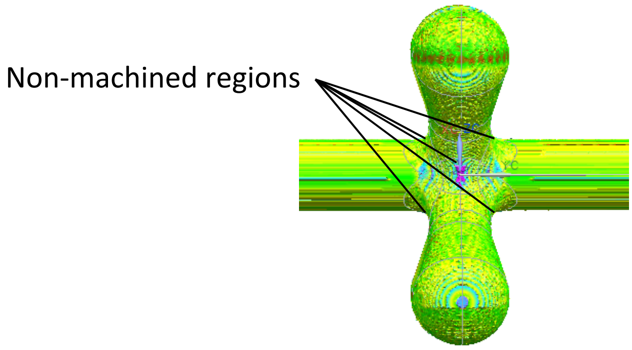


Figure 5.1: Non-machined regions (Li et al. 2006)

This study attempts to show that using multiple tools for finishing operations will improve surface characteristics by minimizing the excess material left on machined parts. Increasing the number of tools will add to the cutting operations as each tool represents one finishing operation. However, machining time is not necessarily going to be extended if these cutters remove material efficiently. Within the cutting direction, all surfaces presented on the part can be translated into several categories. Hence, it is possible to employ different cutter geometries on different surface categories so that the quality can be improved. A distinct methodology developed is defined in the second part of this chapter. The methodology allows cutting tools to be integrated within one orientation in 3-axis milling and considers the implications for process planning. Subsequently, simulations are used to compare several approaches based on single and multiple tools. The results are discussed further by evaluating the volume of excess material calculated by the analysis software. Any effects are highlighted so that further improvements can be considered.

5.2 Methodology

Previous studies have based their criteria for the selection of finishing tools by using the smallest diameter flat end mill. This allows the cutting tool to machine most of the shapes that form the part. Additionally, this common approach simplifies the planning tasks and maintains the feature-free nature of CNC-RM processes. However, there are some drawbacks associated with the use of a single cutting tool. These particularly affect surface roughness and quality of machined parts. Introducing different cutter geometries might be a feasible solution to this problem. However, clear guidelines are required to assign suitable regions for particular cutting tools. Among the critical tasks involved are the separation of cutting regions and the type of tools potentially to be included in the operations. At the same time, the abilities of the CAD/CAM system are fully exploited to run simulations and produce reliable results once the proposed approach has been validated.

5.2.1 Surface classification

During finishing operations, the role of machining is shifted to forming and shaping the part from a predetermined orientations set. Unlike roughing operations that are targeted at bulk material removal, finishing operations are executed at a very minimum depth of cut to remove the material remaining from the previous operations. Machining based on the part surfaces has been successfully implemented earlier in finishing parts built by welding processes through layer deposition methods (Akula et al. 2006). However, the approach involves various tool and surface classifications. Considering machining in a rapid environment, a method developed in this study employed a similar approach but in a convincing way which also eliminated irrelevant setups.

Within each orientation, surfaces presented on the part can be categorized into flat and non-flat surfaces. Flat surfaces represent an area that is perpendicular to the cutting tool whereas the rest of the area can be expressed as non-flat surfaces. The main intention of this classification is to create machining operations for each type of surface using different cutters. Any orientations that contain both flat and non-flat surfaces will require two finishing operations. The first operation works to finish cut the material on flat surfaces using a flat end mill tool. Following this, a second operation is executed to remove material from the rest of the surfaces. In contrast, only one finishing operation is performed if one type of surface is classified. As an example, Figure 5.2 visualizes the categorization of flat and non-flat surfaces within one cutting orientation. Assuming that the cutting is at a 0^{o} orientation, the tool travels downwards and cuts the workpiece from the ZC direction. In this particular direction, the dark grey areas are recognized as flat surfaces because they are perpendicular to the direction of the cutting tool. Thus, the first finishing operation is carried out on these surfaces using a flat end mill. Next, the current tool is replaced with a similar size ball nose end mill. Then, other surfaces appearing as light grey areas are machined through the second finishing operation.

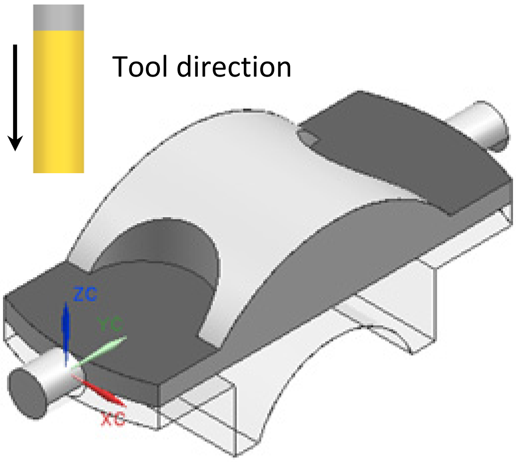


Figure 5.2: Classification of flat and non-flat surfaces in one orientation

5.2.2 Cutting tools adaptability

Basically there are three prominent end mill tools that are widely used in machining processes. These are the flat bottom end mill, an end mill with full radius (ball nose end mill) and an end mill with corner radius (bull nose end mill). The flat end mill is a superior tool to shape the flat bottom and sharp corner features. Meanwhile, a ball nose end mill is suitable for free form shapes that combine various surfaces. The bull nose tool inherits the capabilities and limitations of both tools and is usually used to machine corner radii between a flat bottom and a wall (Krar et al. 2004). However, in this study, only two types of tool are selected to execute finishing operations. The flat end mill precisely machines plane surfaces and generates smaller scallops compared to other tools (Ryu et al. 2006, Elber 1995). Therefore, selection of this tool is quite straightforward to handle flat surfaces, the first type of surfaces classified on the part.

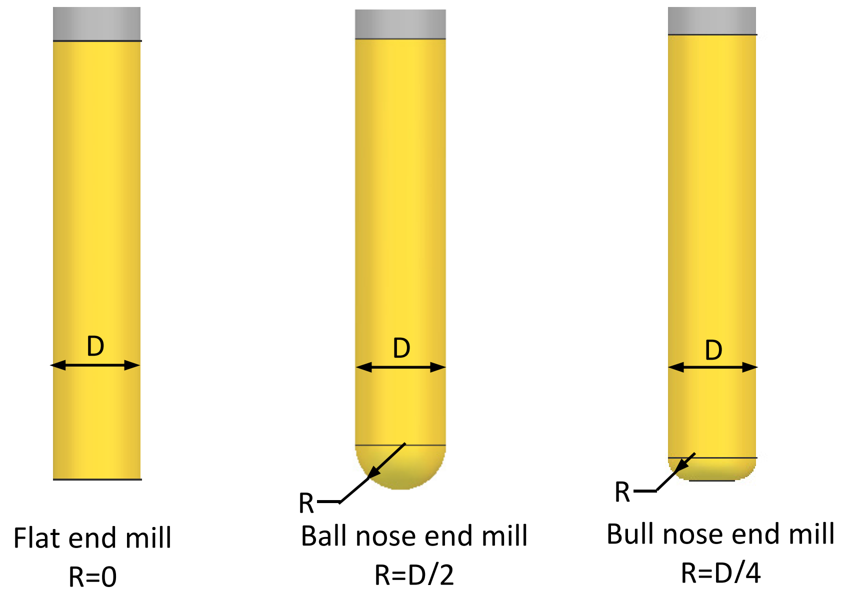


Figure 5.3: Three prominent shapes of end mill tool (Engin et al. 2001)

Meanwhile, the selection of tools to cater for non-flat surfaces requires further review because both available types of cutter possess the same capabilities in different ways. Numerous studies have revealed the potential of ball nose end mills to work on sculptured surfaces especially in die/mould manufacture and they manage to achieve high quality surface finish (Vijayaraghavan et al. 2008, Chen et al. 2005, Elbestawi et al. 1997). The spherical shape on the tip of the tool allows full penetration to occur at any part geometry. However, a dull appearance may be present on the part due to the zero cutting speed at the end point of a ball mill (Liu 2007). On the other hand, a bull nose tool removes a high volume of material and potentially reduces the machining time (Patel 2010). At the same time, it produces a better scallop result if the tool cuts a surface that has a minimum inclination angle. Contradictory to the ball nose tool, the tool geometry causes limited access to certain part features as exemplified in Figure 5.4. This is almost the same situation that limits the accessibility of a flat end mill tool. Since CNC-RM processes work without any knowledge of part features, it is essential to use a finishing tool that grants wide accessibility to the parts. As a consequence, the ball nose end mill is selected to cut non-flat surfaces. Moreover, in a 3-axis milling machine, the ball nose tool can be easily positioned to engage with the part surface and produces more straightforward NC codes (Chen et al. 2008).

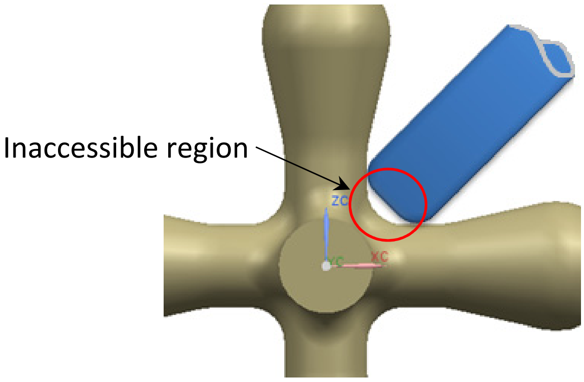


Figure 5.4: Limited accessible for bull nose end mill to cut the material

Similar to the roughing operations, the levels of cutting proceed until the centre of the cylindrical workpiece. However, there is a concern that needs to be addressed while using the ball nose end mill as a finishing tool. The ball nose touches the workpiece at only one contact point at the round tip of the tool. Thus, if the cutting progresses until the centre of the workpiece, a small portion of material is left and needs to be removed in other orientations. This is fine if the part did not contain any limited access areas. However, if a closed area is presented, it will cause difficulty for the ball nose cutter to completely remove the material. The situation is shown in Figure 5.5 where material is left uncut due to the limited cutting levels. In order to overcome this problem, a ball nose tool is instructed to cut down a little further until the side of the cutting tool reaches the centre of the workpiece. By extending the cutting levels, all cutting areas are covered and the part is machined completely. This problem only exists on certain part geometries, but the method is generalized to all finishing operations that utilize a ball nose end mill.

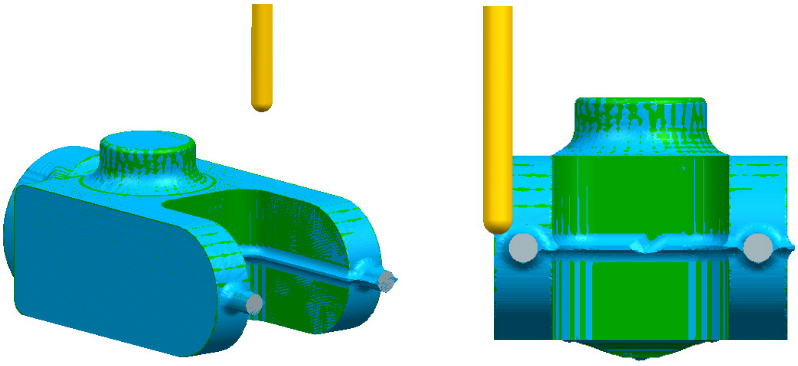


Figure 5.5: Inadequate cutting levels of ball nose tool

5.2.3 Verification processes

Using similar models from the previous study in Chapter 4, the finishing operations are modified to incorporate different tools based on the surfaces contained in the parts. The modifications were carried out manually and include creating a new tool and constructing another finishing operation if two different surfaces exist. Following this, simulations are run while implementing the newly developed roughing approach. The performance of integrating cutting tools is evaluated by focusing on two indicators. Again, machining time is considered as one of the indicators and the other one is based on excess material left on the part once machining has been completed. Machining time can be obtained directly from the NX software, but any excess volume requires further analysis to simulate and extract the result from other software. In this study, CGTech VERICUT® 7.2.3 (CGTech 2012) was used to simulate NC codes from NX and identify the excess volume left on the parts. Recently, this software has been integrated within the same interface as NX and therefore it provides convenient access to verify programs.

In order to estimate the excess volume, the machining program produced is translated into a cutter location source file (.clsf). This file works as a communication tool between NX and VERICUT® software. Since the software is already integrated, the VERICUT® function can be easily activated by selecting the application on the NX toolbar. Prior to commencing the simulation on VERICUT®, a few setups are required. These include defining an output directory, loading the correct .clsf file and determining part and stock. Once simulations have been completed, the '*X-Caliper*' tool is selected to identify relevant parameters which include stock volume, machined volume and current part volume. Meanwhile, the original part volume is measured within the NX interface by using the '*measure bodies*' tool. The excess volume can be calculated by subtracting the current part volume from the original one. Integrating different cutters in finishing operations has been completely implemented in this study. Indeed, results were successfully obtained and it helps to justify the method as a reliable and practical approach.

5.3 Results and Discussion

Simulations were performed to demonstrate the effects of cutting tools used in finishing operations. There are two distinct evaluation criteria based on machining time and excess volume left on the part. To visualize the implications in a wider perspective, these criteria have been compared with other approaches that have been developed previously. Hence, two previous approaches are identified for inclusion in this study. Approach 1 performs machining based on visibility orientations. Approach 2 is based on machining through four roughing orientations and utilized only a single flat end mill. These approaches are compared to the approach developed in this study (Approach 3) that used multiple tools in finishing operations. Table 5.1 to Table 5.4 summarize the results that mainly contain both evaluation criteria. Machining time is recorded in (hour:minutes:seconds) and volumes in mm^3. The cutting parameters are similar to those used in the analyses performed in chapter 4 but in this study, a ball nose end mill is introduced as an alternative cutting tool in finishing operations. In the tables, the amount of material removed from the workpiece is denoted as the machined volume. Meanwhile, the current part value represents the estimated volume of the part once machining has been completed.

Table 5.1: Results for drive shaft model

Approach		Drive shaft		
Criteria		Approach 1	Approach 2	Approach 3
Machining time	h:min:sec	04:31:44	04:13:20	04:02:35
Finishing time		03:10:00	02:38:30	02:28:39
Non-cutting time		00:18:48	00:16:58	00:16:08
Roughing time		01:02:52	01:17:52	01:17:48
Roughing time percentage		23.1%	30.7%	32.1%
Number of operations		7	7	9
Number of tool changes		5	1	5
Cutting orientations		32°-180°-0°	90°-180°-280°-0°-32°-180°-0°	90°-180°-280°-0°-32°-180°-0°
Part volume	mm^3	52729.23		
Stock volume		203517.28		
Machined volume		150272.80	150273.23	150432.83
Current part volume		53244.48	53244.05	53084.45
Excess volume		515.25	514.82	355.22

Table 5.2: Results for knob model

Approach		Knob		
Criteria		Approach 1	Approach 2	Approach 3
Machining time	h:min:sec	04:08:36	03:50:09	03:52:40
Finishing time		02:48:54	02:44:49	02:27:16
Non-cutting time		00:10:43	00:09:11	00:10:20
Roughing time		01:08:59	01:15:04	01:15:04
Roughing time percentage		27.8%	32.6%	32.3%
Number of operations		7	7	7
Number of tool changes		5	1	2
Cutting orientations		180°-45°-315°	90°-180°-280°-0°-180°-45°-315°	90°-180°-280°-0°-180°-45°-315°
Part volume	mm^3	21132.64		
Stock volume		134607.50		
Machined volume		112981.42	112946.97	113203.60
Current part volume		21626.09	21660.63	21403.91
Excess volume		493.45	527.99	271.27

Table 5.3: Results for salt bottle model

Approach Criteria		Salt bottle		
		Approach 1	Approach 2	Approach 3
Machining time	h:min:sec	04:41:44	04:32:02	04:23:26
Finishing time		02:56:03	02:38:44	02:29:33
Non-cutting time		00:12:14	00:11:57	00:12:28
Roughing time		01:33:27	01:41:21	01:41:26
Roughing time percentage		33.2%	37.3%	38.5%
Number of operations		6	7	9
Number of tool changes		5	1	5
Cutting orientations		45°-180°-270°	0°-90°-190°-270°-45°-180°-270°	0°-90°-190°-270°-45°-180°-270°
Part volume	mm^3	34081.83		
Stock volume		111176.19		
Machined volume		76700.20	76676.80	76845.85
Current part volume		34475.98	34499.39	34330.33
Excess volume		394.15	417.56	248.5

Table 5.4: Results for toy jack model

Approach Criteria		Toy jack		
		Approach 1	Approach 2	Approach 3
Machining time	h:min:sec	03:32:56	03:25:22	03:21:42
Finishing time		02:28:35	02:16:04	02:12:44
Non-cutting time		00:13:56	00:14:06	00:13:44
Roughing time		00:50:25	00:55:12	00:55:12
Roughing time percentage		23.7%	26.9%	27.4%
Number of operations		8	8	8
Number of tool changes		7	1	1
Cutting orientations		49°-140°-228°-320°	50°-140°-240°-320°-49°-140°-228°-320°	50°-140°-240°-320°-49°-140°-228°-320°
Part volume	mm^3	7517.12		
Stock volume		117432.01		
Machined volume		109660.05	109662.15	109792.30
Current part volume		7771.96	7769.86	7639.71
Excess volume		254.84	252.74	122.59

Based on the tables, there are significant differences between Approach 3 which is based on this study compared to Approaches 1 and 2. Out of the four models, three produce a significant decrease in total machining time by implementing Approach 3. This approach utilized multiple tools in finishing cuts, and hence increases the number of operations. But, the results indicate that adding machining operations does not necessarily generate longer machining times. It most likely depends on how effectively cutting tools remove material from part surfaces. Roughing times for Approaches 2 and 3 shared similar values as both employed the same roughing strategy through four cutting orientations. The most striking results can be seen for the excess volume information for each model. Accordingly, all models demonstrate minimum excess volume in Approach 3. By assigning a specific tool to a particular surface, the ranges of excess volume reduce to about 0.7% to 1.6% of total part volume. Finishing operations that depend on a single tool reveal slightly higher excess volumes of between 0.9% and 3.3%. As a consequence, more excess material should be expected to be left on the workpiece if the finishing operations solely depend on a flat end mill cutter.

5.3.1 Implications for machining time

This study set out with the aim of assessing the implications of using multiple tools in finishing operations performed on a 3-axis milling machine. It focused on the practicality of integrating the tools based on classified surfaces in one cutting direction. Based on virtual machining verification, the flat end mill tool managed to remove material effectively on flat surfaces. However, the tool geometry caused a step appearance when dealing with contour and inclined surfaces. Contradictorily, the ball nose cutter was capable of dealing with non-flat surfaces but formed a noticeable scallop effect on flat surfaces. Considering these capabilities and weaknesses, integrating these tools to work on different surfaces is a viable approach to enhance part quality. The results gathered and shown in the tables clearly reflect the benefits of using both flat and ball nose end mills in finishing operations.

The results of this study will now be compared to the findings from previous work represented in Approach 1 and 2. The majority of the study models consistently indicate a reduction of machining time compared to single tool approaches. Most of the savings come from the decreasing of finishing operations time due to effectiveness of cutting tools in removing the material. Consequently, this leads to a reduction of the total machining time as the roughing time remains constant between Approaches 2 and 3. Depending on part geometries, the savings can be as much as 30 minutes. For example, the results for the drive shaft model in Table 5.1 indicate that Approach 3 managed to reduce machining time by about 11 minutes compared to Approach 2 and about 29 minutes compared to Approach 1. Both Approach 1 and Approach 2 rely on a single flat end mill to execute the finishing operations. Nonetheless, there are some models where only a small reduction in machining time is obtained, for instance the toy jack model where cutting time was reduced by about 3-10 minutes. In this case, only a ball nose end mill was used in finishing operations as all the cutting orientations consist of non-flat surfaces. From the production perspective, minimizing machining time in producing one part can be multiplied further if the same part is produced on a large scale. Therefore, a small reduction in machining time can influence the production cost significantly depending on the quantity produced.

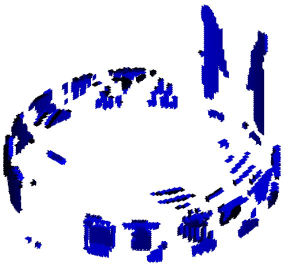
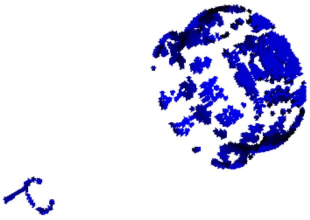
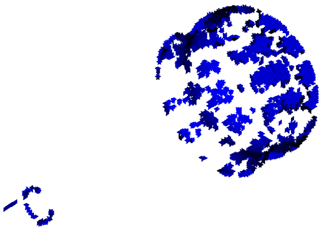
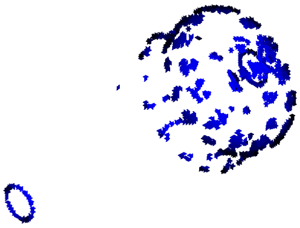
The approach developed in this study has adopted the roughing method discussed in Chapter 4. So, there are four orientations allocated in the early stage of the process for roughing operations. This is followed by finishing orientations that are based on part visibility analysis. Integrating different cutters for finishing operations did not affect the number of orientations used, but it did influence the number of operations and tool changes. If there are flat and non-flat surfaces present in one finishing orientation, the process requires two cutting operations with different tools and a tool change is needed between operations. For example, there are two orientations in the salt bottle model that contain flat and non-flat surfaces. Therefore, a total of four operations are executed and equally distributed between the two orientations. In total, the program will create five finishing operations including the tool changing instruction when necessary. Meanwhile, Approach 1 that used a single cutting tool required three finishing operations and five tool changes as the operations alternate between rough and finish cuts. Despite a little complication for process planning, integrating finishing tools seem to be a viable solution to enhance removal rates and part quality.

5.3.2 Machining excess material

Prior studies have noted the capabilities of ball nose end mills in machining sculptured surfaces and producing high quality parts (Vijayaraghavan et al. 2008, Elbestawi et al. 1997, Engin et al. 2001). Particularly in this application, classifying cutting tools based on part surfaces during finishing operations managed to minimize the amount of excess material. Surprisingly, some of the models studied show a considerable reduction as can be seen in the knob model where the excess volume decreased from around 500mm^3 down to 270mm^3. The results of this study consistently indicate that excess volume was reduced compared to a single cutting tool approach. Fundamentally, the amount of excess volume left is highly dependent on the way finishing operations are executed. These include the depth of cut, number of finishing passes, cutting patterns etc. However, in this study, all parameters remained constant except for the type of cutting tools employed. Thus, the decreasing excess material recorded is solely influenced by the combinations of cutting tools.

The result may be explained by the fact that the ball nose end mill is capable of removing material on non-flat surfaces and minimizing the step appearance. According to the excess material diagrams shown in Table 5.5, the remaining uncut materials are highly concentrated on non-flat surfaces for Approach 1 and 2. In contrast, most of the materials on these areas for Approach 3 have been removed effectively by a ball nose tool. In other words, the staircase effects on non-flat regions are minimized. Therefore, there is decreasing trend in the percentage of excess volume in relation to current part volume between Approaches 1 and 2 and Approach 3. At the same time, the performance of flat end mills cutting flat surfaces is maintained and this has intensified the amount of material removed during finishing operations.

Table 5.5: Excess material distribution diagrams on studied models.

Drive shaft		
Approach 1= 0.97%	Approach 2= 0.97%	Approach 3= 0.67%
		
Knob		
Approach 1= 2.28%	Approach 2= 2.44%	Approach 3= 1.26%
		
Salt bottle		
Approach 1= 1.14%	Approach 2= 1.21%	Approach 3= 0.72%
		
Drive shaft		
Approach 1= 3.28%	Approach 2= 3.25%	Approach 3= 1.61%
		

Combinations of these tools succeed in keeping excess material at a minimum. However, there was one unanticipated finding from the observation of virtual cutting simulations. In the case where the sacrificial support is attached to a flat vertical surface, the ball nose tool encountered accessibility problems when trying to fully machine the supports. Thus, a fillet shape that replicates the roundness of the cutting tool tends to form on the edge of the support and part. Conversely, the previous approach that used a flat end mill manages to reach this sharp edge but it only occurred on the area perpendicular to the cutter direction. Unfortunately, the fillet shape is still visible on the rest of the connection area. Figure 5.6 illustrates excess material formed on the connection edge between the sacrificial support and the part surface. To date, there are no specific methods developed to eliminate this problem. However, a strategy of selecting small cutters manages to minimize the effect as it forms a small excess fillet on this area. Contradictorily, using a large diameter tool will increase the excess volume and leads to inefficiency during post cutting operations.

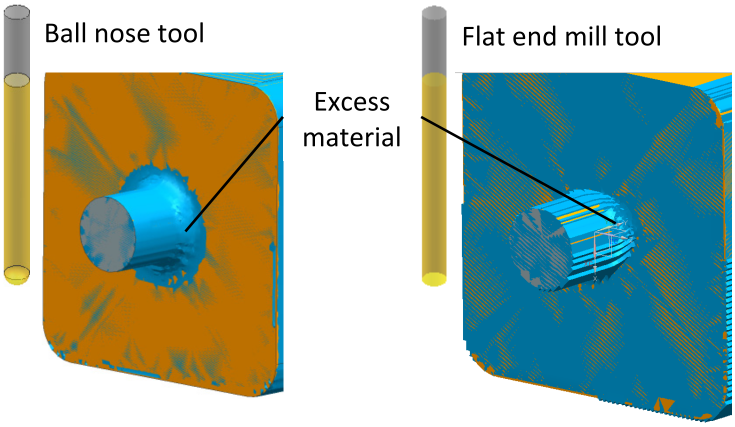


Figure 5.6: Formation of excess material at the sacrificial support edge

Since the machining is performed in various orientations, some considerations should be underlined while developing the procedure to build the machining program. Integrating tools during finishing operations requires identification of flat and non-flat surfaces. This classification is not based on normal horizontal and vertical orientations of the part. But rather it would depend on which orientations or directions the tool engages with the workpiece. Therefore, flat surfaces are not only present on vertical and horizontal surfaces but also include the inclined surfaces if perpendicular to the cutting tool direction. Due to this circumstance, it is important to preserve some flexibility and communication medium in the planning program so that classification of surfaces can be carried out correctly. After all, integrating tools in finishing operations has important implications for part quality. The previous method employed a single tool and caused a step appearance on the part as can be seen widely in additive processes. Even though it can be reduced by minimizing the cutting depth, the effect is still visible and furthermore it would increase machining time. The amount of excess materials calculated from this study indirectly portrays the level of quality that can be achieved by integrating the tools. However, real machining experiments are required to examine the effectiveness of the proposed method.

5.4 Summary

This chapter has revealed the implications of using multiple tools for finishing operations in CNC-RM processes. The main goal of the current study was to improve part quality by minimizing excess material left once machining had been completed. Overall, the results of this investigation show that using different cutting tools on flat and non-flat surfaces manages to keep the machined part volume close to the design volume. In other words, remaining uncut materials left on the part are reduced if different tools are adopted during finishing operations. Moreover, depending on part geometries, it also saves manufacturing time by decreasing the time spent for finishing operations. Machining operations developed in the previous chapter that were based on a single cutter are also included in this study. Since both studies utilized similar test models, comparison can be made in terms of machining times and excess volumes to highlight the effectiveness. Taken together, the results suggest that the method proposed in this study is capable of enhancing part appearance and quality. Further work is required to validate the approach in real machining operations. This permits an extensive assessment by examining roughness characteristics exhibited on part surfaces that have been machined with different cutters. Moreover, an effective method needs to be identified to incorporate the approach in the CNC-RM planning processes.

Classification of surfaces must be guided properly without complicating the process flow. Hence, it is possible to add another criterion while determining the finishing orientations set. Rather than just focusing on surface visibility, the presence of flat and non-flat surfaces can also be considered which later, reflects the type of tools used and the quality of the machined part. Finally, cutting operations can be created based on the type of cutting tool selected for the process.

CHAPTER 6

IMPROVING FINISHING ORIENTATIONS FOR NON-COMPLEX PARTS: AN ALTERNATIVE APPROACH

6.1 Introduction

The machining orientations set is an important component in CNC-RM operations and plays a key role in establishing the process. Since the workpiece is being machined from various directions, some consideration of the determination of these orientations is required. The issue of thin web formation has received considerable attention throughout the development phases of this approach. In previous developments, the establishment of cutting orientations is strictly bound with the thin webs avoidance requirement. During roughing operations, machining from 0^{o}, 135^{o} and 225^{o} manages to avoid thin webs and to remove the bulk of material from the workpiece (Renner 2008). Therefore, machining from a minimum of three orientations is most likely to be adopted to comply with the requirement. To further the analysis, these cutting orientations are generated from a customised algorithm that studies the visibility of the part surfaces. Basically, the analyses involve identifying visibility ranges, calculating blocked ranges and finally proposing a minimum set of orientations that manage to cover all part surfaces (Frank et al.

2006). In the case of machining complex parts, the numbers of orientations are probably increased and become more than three orientations.

Most of the time, machining is prevented from taking place from two directly opposite orientations even for non-complex parts. Therefore, the only way to define the orientations is by examining the parts through visibility analysis. Certainly, this is essential for parts containing complex shapes where the features are only visible in specific orientation ranges. However, for non-complex parts, the orientations can be easily interpreted as there is no restricted access for cutting tools. The differentiation between complex and non-complex parts can be relied on to determine the orientations required to achieve the final geometry. If there are many closed regions that are only accessible from specific orientations, the part has complex shapes and requires more than two cutting orientations. On the other hand, if all the geometries can be machined within two cutting orientations, the part is considered as non-complex. Recent developments have suggested that the splitting of roughing and finishing operations succeeds in eliminating thin material formation. On top of this, it imparts some flexibility in finishing operations where cutting directions can be widely selected and it may be possible to machine from two orientations. This study attempts to show the implications of machining with only two finishing orientations. The results produced will become an indicator to decide whether it is an alternative method to perform finishing operations in rapid machining processes.

6.2 Machining through two finishing orientations

The CNC-RM approach is capable of machining a wide range of components and materials. As an indexer is used to provide a 4th axis of rotation, appropriate cutting orientations are required to fabricate the part. Determining cutting orientations based on part visibility is definitely a reliable method to ensure all surfaces are machined. However, orientations proposed must comply with the thin web avoidance rule and thus at least three orientations are typically used to create parts. Using this approach, it is expected that any tendency for the formation of thin webs will be eliminated but further assessments need to be conducted. A problem may arise if any two orientations fall in directly opposite directions where there is a possibility of forming thin material during machining. In order to visualize the problem, 0°, 130° and 180° cutting orientations are taken as an example. During the third orientation at 180°, the cutting tends to form thin material on the other side of the workpiece as illustrated in Figure 6.1. Therefore, it is important to revise the distribution of the orientations even if three cutting directions are involved.

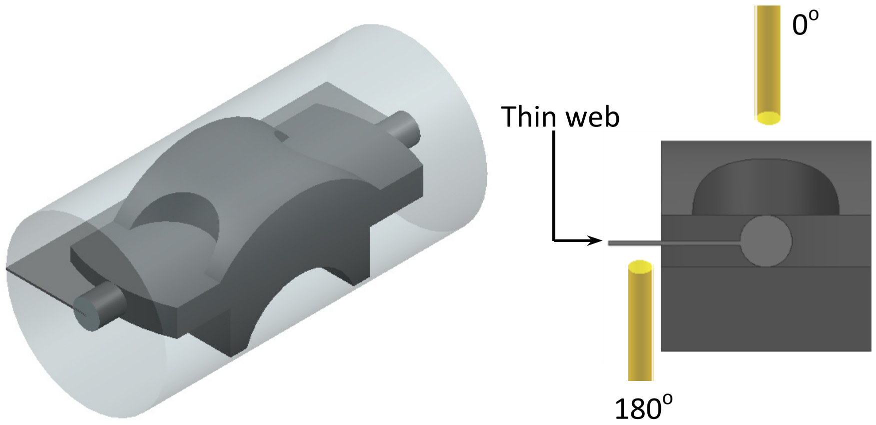


Figure 6.1: Thin web formed during the third cutting orientation

An approach that performs all roughing operations at the beginning of the process and is then followed by finishing operations seems a viable method of eliminating thin webs. This distinct approach conserves some flexibility for roughing and finishing orientations as they are not bound between each other. Initially a series of roughing operations will cut the workpiece until a predetermined thickness of material is left on the part. The stock thickness depends on program settings and in this study a 1mm layer of stock is left on the part. Figure 6.2 shows the stock material left which will be removed through finishing operations. As a result, it is possible to simplify finishing orientations and work with two opposite orientations. Nonetheless, this is only applicable for non-complex parts. If complex features are present, then more orientations are required and these need to be defined based on visibility analysis.

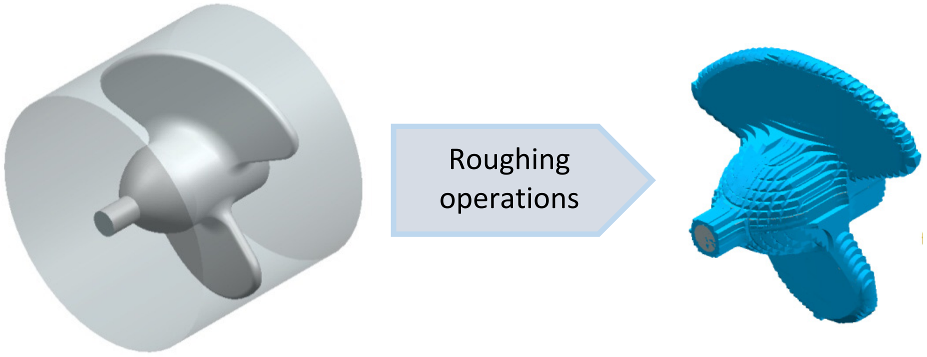


Figure 6.2: Remaining material left after roughing operations

It is possible to use this approach with three out of the four models used in previous chapters. These are the drive shaft, salt bottle and knob models. Observing the part features, it is easy to formulate the minimum orientations that cover all surfaces. Thus, finish cuts from two orientations can be implemented on these models. In this study, the two finishing cut orientations were selected based on opposite directions and were required to cover all part surfaces. There are probably other orientations sets that could provide the same coverage as well. For example, orientations of 45^{o} and 225^{o} are capable of providing wide coverage on the salt bottle model. Similarly, this model also can be machined from 0^{o} and 180^{o} as these orientations allow cutting on all surfaces. The purpose of this study is not to find optimum orientations but rather to evaluate the implication of using two cutting directions for finishing operations. Therefore, it is justified to select any two finishing orientations that are capable of machining the parts completely. The selection of cutting orientations is quite straightforward but later it will influence the type of cutters used depending on the classifications of the surfaces. Figure 6.3 visualizes finishing orientations used on the selected models.

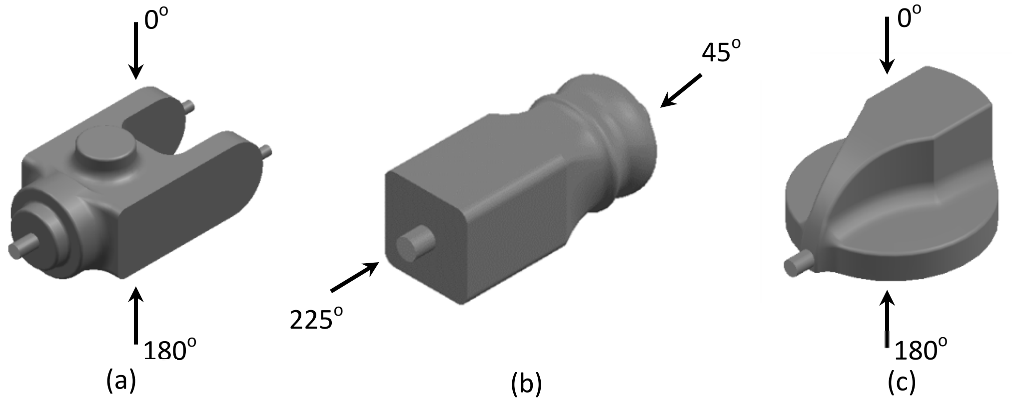


Figure 6.3: Two finishing orientations proposed for (a) drive shaft, (b) salt bottle and (c) knob models

6.3 Results and discussion

In order to validate the approach, a machining program for each model was developed. The roughing operations were performed through a set of four optimum orientations while the finishing operations were based on the two opposite orientations proposed. Similar to the previous simulation studies, the efficiency is evaluated by examining the machining time and excess volume left on the part. Table 6.1 summarizes the simulation results for selected models. The column section represents the models and being divided based on number of finishing orientations used. The first column of finishing orientations duplicates the result of Approach 3 from Table 5.1, Table 5.2 and Table 5.3 in chapter 5 where the orientations were based on part visibility and fulfils the thin web avoidance requirement. Meanwhile, the second column represents the results obtained after simplifying the orientations into two cutting directions only.

Table 6.1: Comparison between three and two finishing orientations

Model		Drive shaft		Salt bottle		Knob	
		3 orientations	2 orientations	3 orientations	2 orientations	3 orientations	2 orientations
Number of finishing orientations		32°-180°-0°	180°-0°	45°-180°-270°	45°-225°	180°-45°-315°	180°-0°
Machining time	hours:minutes:seconds	04:02:35	03:36:08	04:23:26	04:10:07	03:52:40	03:21:24
Finishing time		02:28:39	02:05:21	02:29:33	02:19:18	02:27:16	01:59:17
Non-cutting time		00:16:08	00:13:00	00:12:28	00:09:23	00:10:20	00:07:02
Roughing time		01:17:48	01:17:48	01:41:26	01:41:26	01:15:04	01:15:04
Number of operations		9	8	9	6	7	7
Number of tool changes		5	4	5	1	2	2
Part volume	mm^3	52729.23		34081.83		21132.64	
Stock volume		203517.28		111176.19		134607.50	
Machined volume		150432.83	150436.58	76845.85	76897.50	113203.71	113222.73
Current part volume		53084.45	53080.71	34330.33	34278.70	21403.79	21384.77
Excess volume		355.22	351.48	248.5	196.87	271.15	252.13

Comparisons between both approaches that differ in terms of number of finishing orientations were made by evaluating the machining time and excess volume. It is apparent from Table 6.1 that finish cuts using two orientations produce a significant result in terms of machining time. Referring to the simulation study, all models point to a similar trend where the cutting time decreases compared to a three finishing orientations approach. Most of the saving is contributed by the reduction of finishing cutting time. Hence, reducing the number of finishing orientations did affect the cutting time. This finding supports previous research that aims to minimize the number of orientations because it assumed that more orientations tend to increase the cutting time (Frank et al. 2006). However, this is only applicable to finishing orientations as roughing processes have already been executed from four cutting directions. As mentioned earlier, the number of operations still relies on the type of surfaces present on the part. The salt bottle model indicates a decreasing number of operations because only non-flat surfaces exist in both directions. Thus, a ball nose end mill is selected to perform the cutting operations. In contrast, the knob model requires the same number of operations even though the orientations decrease. Flat and non-flat surfaces are contained in one of the orientations and this needs two cutting operations to finish cut the part. This caused the number of operations to remain constant.

The results of this study also reveal some correlation between finishing orientations and remaining uncut material. The excess volume decreased when two finishing orientations were used. However, the differences are not really significant as both approaches have already adopted different cutting tools in finishing operations. The excess volume was only reduced by 4mm^3 in the drive shaft model and the highest reduction is only about 50mm^3 recorded in the salt bottle model. Since the machining was performed in two opposite directions, there is a high tendency for excess material to be left by a ball nose end mill if the tool cuts until the centre of workpiece only. Therefore, cutting levels must be extended further so that there is an overlap distance between the orientations. If there are only flat surfaces present in both directions this problem can be neglected as only flat end mills were used. After all, it is not always the case where the part contains only flat surfaces in both orientations. Therefore, it is important to consolidate standard cutting levels in the program so that finishing operations are performed effectively within the two orientations.

6.4 Summary

This study proposed an alternative method of determining the finishing orientations for simple and non-complex parts. Returning to the question posed at the beginning of this study, it is now possible to state that using two finishing orientations influences the process in certain aspects. The findings suggest that, in general, reducing the number of finishing orientations manages to minimize the cutting time but does not produce a notable effect on excess material. Executing roughing operations in independent orientations sets had triggered the possibility of enhancing the way finishing operations are performed in the CNC-RM process. Parts that do not contain any complex features can be directly fabricated through two opposite cutting directions that would be expected to cover all surfaces. Therefore, visibility analysis can be excluded in finding the cutting orientations as it can be directly proposed based on user interpretation. However, as an alternative method, visibility analysis is still required if complex features are present and cutting tools are not able to cover all surfaces within the two orientations. An issue that was not addressed in this study is a definite classification of complex and non-complex parts. Based on common interpretation, it is possible to implement this approach on any parts where all surfaces are exposed only to two cutting directions. A further study could possibly focus on establishing the guidelines to select an optimum two finishing orientations set. This is important as the combination of the two orientations is proven to influence the efficiency of the cutting operations.

CHAPTER 7
MACHINING EXPERIMENTS

7.1 Introduction

The performance of CNC milling machines in rapid applications has received considerable attention and the simulation studies described in previous chapters have pointed out some possible approaches to optimizing CNC-RM processes. The first approach is focused on improving the roughing process and leads to the implementation of a new independent orientations set. Theoretically, this approach increases time spent on rough cuts but influences later operations to decrease total machining time. A second development suggests the use of different cutting tools in finishing operations. Generally, this approach requires the user to assist the program in classifying the part surfaces presented within one cutting direction. The effects can be seen in the reduction of excess volume left on parts which indirectly represents the level of quality achieved. Finally, an approach using finish cuts from two cutting directions was studied. In implementing the first approach, orientations for finishing operations become more flexible and are not bound in with thin web avoidance requirements. Therefore, it is feasible to apply two cutting orientations especially for non-complex parts. As discussed in chapter 6, the results indicate that machining time can be reduced further although the excess volume is not really affected by this approach.

Essentially, all the approaches developed need to be verified further by conducting machining trials so that cutting operations can be examined in terms of the process efficiency and quality of the machined parts. The results can also be used to confirm the findings gathered from simulation studies. Any unexpected outcomes can be analysed and corrective measures can be taken on the approach itself or in the process planning. In these experiments, in addition to verifying the developed approaches, the programs that were created to assist planning tasks were also evaluated. It is crucial to make sure the output of the programs is correct so that cutting processes can be executed without any mistakes. The rest of the chapter will highlight the methodology and outcomes of these experiments focusing on assessing the developed methods in the context of real machining and also examining the quality of the parts produced. There are three main objectives of the experiments:

i. To validate the approach that utilized four standard orientations for roughing operations. Based on the process sequence, all roughing operations will be executed first and then be followed by finishing operations.

ii. To observe the effects of using single and multiple tools during finishing operations. The findings are evaluated in terms of part quality and machining efficiency.

iii. To evaluate the practicality of the two finishing orientations approach. This approach will be incorporated in the process planning program if it improves process efficiency.

7.2 Methodology

The experiment starts by developing the part or model to machine. In this case, two models were developed which are different from the models used in the simulation studies. The reason for this was to expand the analysis and evaluate the adaptability of the approaches developed with parts that have different kinds of features. Also, the approaches can be examined from the perspective of the overall process starting from the planning stage right through to completion of machining. Figure 7.1 illustrates the selected models which consist of a crane hook (model 1) and a vehicle gear knob (model 2). A wide range of geometrical features are contained within these parts including flat and non-flat surfaces, and so they are suited to the approaches developed. Dimensional sketches of these models can be found in Appendix B. Previous research has already proven the ability of CNC machines with the use of an indexable device to manufacture a wide range of products (Frank 2003). This experiment is more focused on validating the approaches designed to improve the process, and the two selected models are sufficient to demonstrate the implications.

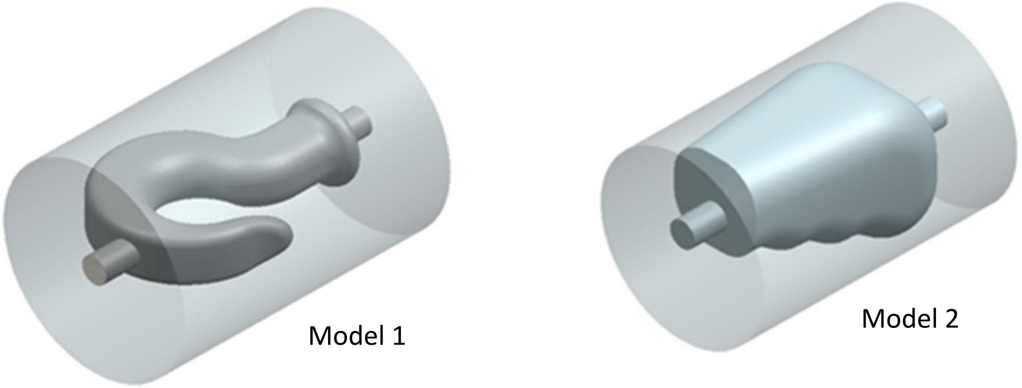


Figure 7.1: Crane hook (model 1) and vehicle gear knob (model 2)

7.2.1 Setup procedures

Prior to commencing the machining, initial analysis is conducted to determine an optimum orientations set for roughing operations. Finishing orientations are decided by referring to previous studies that were based on part visibility and obeyed certain requirements (Frank et al. 2004). Certainly, the machining must proceed from at least three directions so as not to form any thin material during the process. Based on assumptions stated in section 4.2, a finishing orientations set is define for each of the models. As a consequence, 0^o-140^o-250^o-180^o has been selected as the finishing orientations set for the crane hook model whereas 0^o-120^o-240^o was chosen for the vehicle gear knob model. In order to assist the planning phase, the first program was developed to analyse the parts and identify an optimum roughing orientations set. These orientations are formulated from the series of machining simulations that analysed all possible ranges of cutting directions. All cutting parameters must be defined prior to building the machining operations.

Table 7.1 summarizes the machining data for both models that was used as inputs for the simulation program. Spindle speeds and feed rates are already embedded in the program and are generated automatically based on the size of the tool used. The relation between cutting tool size and machining parameters is described in section 8.2. The simulation starts by creating the machining program using the default values 0^{o}-90^{o}-190^{o}-270^{o}. Then, this value is shifted accordingly based on the analysis range defined in the program. The crane hook model requires the program to simulate from 0^{o} to 360^{o}, whereas simulation for the vehicle gear knob is from 0^{o} to 180^{o} only as it is an axi-symmetrical shape and the range 180^{0} to 360^{0} would produce identical results. Unlike earlier simulation studies, the analysis conducted in this experiment covered all possible cutting directions. If the analysis ranges from 0^{o} to 180^{o}, there will 180 cutting times produced and recorded. The program used is capable of running the simulation continuously based on the inputs given. Total machining times are recorded for each direction and are compiled once the whole analysis is completed. The data is then published in excel format where the times can be simply sorted from the shortest to longest.

Table 7.1: Machining data used as input for the simulation program

Machining parameters	Model 1: Crane hook	Model 2: Vehicle gear knob
Material	Aluminium bar	
Cylindrical stock size	(Ø60 x 150) mm	(Ø40 x 130) mm
Sacrificial support size	Ø10 mm	Ø8 mm
Finishing orientations set	0^{o}, 140^{o}, 250^{o}, 180^{o}	0^{o}, 120^{o}, 240^{o}
Roughing operations		
Tool size	Ø12.0 mm	Ø10.0 mm
Depth of cut	2.0 mm	1.0 mm
Spindle speed	1591.0 rpm	1909.0 rpm
Feed	400.0 mmpm	400.0 mmpm
Finishing operations		
Tool size	Ø8.0mm	Ø6.0 mm
Depth of cut	0.2 mm	0.1 mm
Spindle speed	2387.0 rpm	3183.0 rpm
Feed	400.0 mmpm	400.0 mmpm

The orientations set that represents the lowest machining time is denoted as the optimum orientations set to execute roughing operations. Then, the machining program is rebuilt by using the proposed roughing orientations which later produces the codes that are used to run the machine. As a precautionary measure, further assessments are conducted to verify the codes generated. A first stage assessment utilizes VERICUT® software to detect any possible defects on the part. It is also used to estimate uncut material left on the part after machining has been completed. The codes are then verified using the WinMax® desktop program. This is similar to software used on Hurco VM1 3-axis CNC vertical milling machine but it is installed and run on the computer. Hence, the operations can be simulated based on the real machine controller and this allows error detection earlier before cutting processes begin. Since new approaches are introduced in this experiment, all these assessments are essential to ensure that the cutting program runs properly without any unexpected problems. The flow chart in Figure 7.2 shows the procedures implemented in this experiment.

7.2.2 Machining setup

Three machining trials were run for each model. These trials are different in terms of machining approach, orientations set and cutting tools used in finishing operations. The rationale for these differences is to explore the advantages and weaknesses of each approach. The first trial (Trial 1) will machine the part based on the original approach developed to adapt CNC machines to rapid processes (Frank 2003). In this trial, machining is performed based on orientations proposed by visibility analysis. Therefore, roughing and finishing operations are executed alternately within one cutting direction. Only flat end mills were used to machine the parts but the size was different for roughing and finishing operations. It is important to bear in mind that during finish cuts for the vehicle gear knob model, the depth of cut is decreased to 0.07mm from 0.1mm. Since the first trial employs a single cutting tool, this modification is carried out particularly to test how much improvement can be achieved by minimizing the finishing depth.

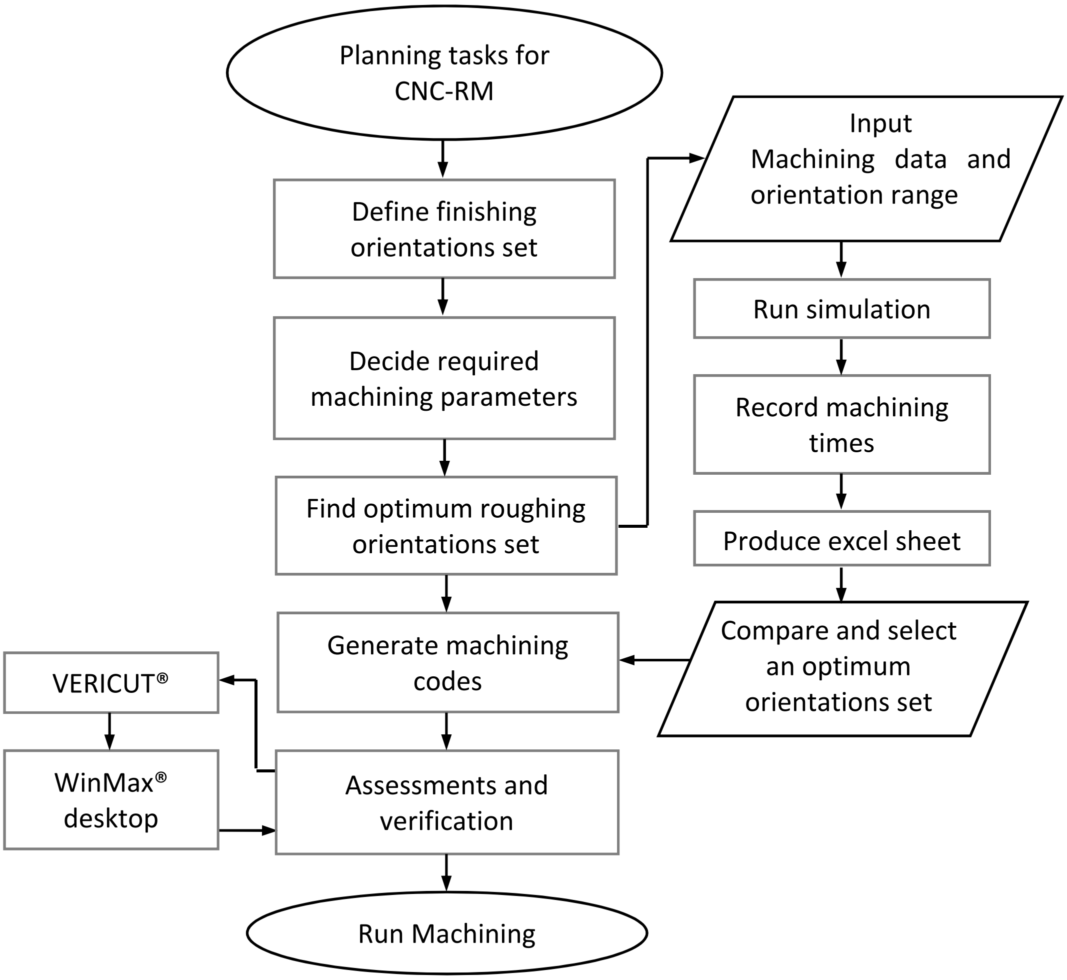


Figure 7.2: Setup procedures before machining the models

Unlike the first trial, the second (Trial 2) and third (Trial 3) trials employed the approaches developed in this research. The trials started by commencing all roughing operations through the four optimum cutting directions. Furthermore, these trials also integrated different types of cutting tools during finishing operations. Hence, flat and ball nose end mills were utilized to cater for flat and non-flat surfaces in predetermined cutting orientations. The only difference between the second and third trials is the number of finishing orientations used. Finishing operations in the second trial machined the part based on orientations suggest by the visibility algorithm as adopted in first trial. In contrast, the third trial simplifies the finishing operations to work within two orientations only. Since both models did not have any inaccessible areas or regions, all surfaces are exposed and can be cut from two orientations. Overall, there are three machining programs developed for each model and that are transferred to the machine controller to machine the parts.

In order to execute the cutting process on a CNC machine, some routine setups are required. Figure 7.3 shows the workpiece setup on the machine. These include:

i. Attach and calibrate indexable device on the machine

ii. Preparation of workpiece. A small hole is drilled at one end of the cylindrical workpiece and is used to locate the pin properly and firmly hold the workpiece

iii. Setup the machine coordinate system (MCS) so that it tallies with the coordinates in the program

iv. Prepare necessary tool and insert in the tool holder. This will assist the tool changing process during machining

v. Rotate the indexable device to the correct value according to the orientations set used in the program.

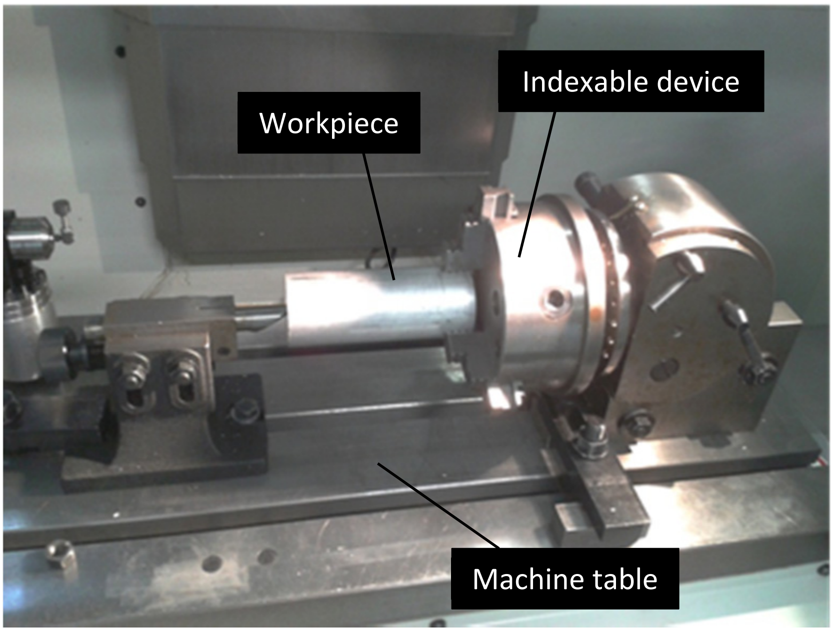


Figure 7.3: Machining setup for CNC-RM processes

7.3 Results and discussion

Generally, the results are summarized into two sections. The first section highlights the simulation results which include the roughing orientations analysis and estimated cutting times calculated by the program. Additionally assessment of the excess volume of material is also incorporated in this section. The second section discusses the machining outcomes according to the adopted approach. Visual inspection is carried out on each part and roughness analyses are performed on selected regions. Finally, the problems raised while conducting the experiment are discussed and effective solutions to improve the process are proposed.

7.3.1 Simulation outcomes

7.3.1.1 Optimum roughing orientations set

Prior to generating the machining codes, simulation is conducted to identify the optimum orientations set for roughing operations. The processing steps of this analysis are shown in Figure 8.6. These values will be used as cutting directions to perform the roughing operations on particular parts. The orientations used reflect the machining time generated from the simulation as recorded in Table 7.2. For model 1, each orientation in steps of 1^0 in the range 0^o to 359^o provided different cutting times. The data generated is recorded in an excel file and thus it can be sorted in ascending order based on machining time. As a result, the orientations set 181^o-271^o-11^o-91^o is denoted as the optimum roughing orientations set for the crane hook model. Total cutting time estimated to machine this part is about 6 hours 15 minutes based on the simulation program.

Table 7.2: Optimum roughing orientations set for crane hook

Orientations (^{o})	Machining time (hour:min:sec)	Orientations (^{o})	Machining time (hour:min:sec)
181	06:14:13	274	06:26:53
270	06:17:09	275	06:26:57
182	06:18:43	264	06:27:16
180	06:20:43	273	06:28:01
79	06:21:42	269	06:28:10
271	06:22:23	75	06:29:39
265	06:23:29	185	06:29:56
80	06:23:43	343	06:30:18
183	06:24:19	174	06:30:21
179	06:24:33	169	06:30:28

For the vehicle gear knob model (Table 7.3), the orientations set 180^o-270^o-10^o-90^o gives minimum machining time and is selected as the roughing cutting directions. Using these orientations, machining time can take up to 5 hours and 50 minutes. The results summarized in the tables only contain the first 20 orientations that indicate minimum machining time. It should be emphasized that in this simulation, machining times proposed for both models are based on a single tool approach without any alterations on the type of cutter used.

Table 7.3: Optimum roughing orientations set for vehicle gear knob

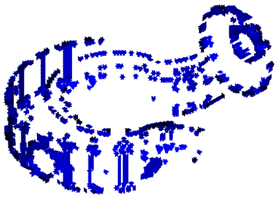
Orientations (^{o})	Machining time (hour:min:sec)	Orientations (^{o})	Machining time (hour:min:sec)
180	05:50:48	26	06:05:47
0	05:56:28	119	06:05:54
148	06:02:41	125	06:05:58
152	06:02:49	32	06:06:07
45	06:04:37	154	06:06:19
145	06:04:52	38	06:06:47
44	06:04:57	46	06:06:51
144	06:05:25	150	06:06:57
40	06:05:35	48	06:07:02
42	06:05:44	36	06:07:18

7.3.1.2 Simulation results based on machining trials

By utilizing the optimum roughing orientations produced, machining operations for trials two and three are developed. Table 7.4 includes the results obtained for all three machining trials based on the crane hook model. It is apparent from this table that trial 3 can be performed with less machining time compared to the other trials. The cutting processes took about 4 hours 33 minutes which is slightly less than trial 2. However, in comparison to trial 1, it is substantially reduced and managed to save about two hours machining time. The machining times predicted later for trial 2 and 3 are different because these trials adopt multiple tools during finishing processes. The main factor that caused the differences is that the finish cutting times change according to the tools and surfaces on parts. Roughing operations times remain the same between the trials because similar optimum orientations sets were used.

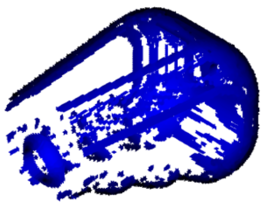
In terms of excess material left after machining, trial 1 indicates a minimum amount, but, based on the excess volume diagram, most of the material is distributed on the surfaces of the part and may affect the roughness value later. In comparison, trial 2 and 3 indicate slightly higher excess volume that is mostly concentrated on the sacrificial support structure as shown by the red circles on the diagrams in Table 7.4. However, the excess volume in important regions on part surfaces is minimum compare to trial 1. Basically, the reason for the concentration is because of the use of a large ball nose tool to cut the area. Curved surfaces at the tool cutting edge caused restrictions in shaping the sacrificial support further and form the excess volume on this area. Using a smaller tool size would minimize the implications and leave a reasonable volume to remove during post-processing. Nonetheless, the uncut materials in this area are not really obvious in trial 1 as a flat end mill tool was used during finishing operations.

Table 7.4: Simulation results for model 1

Trials / Criteria		Crane Hook (Model 1)		
		Machining Trial 1	Machining Trial 2	Machining Trial 3
Machining time	hour:min:sec	06:48:30	04:42:05	04:33:51
Finishing time		05:19:09	03:13:21	03:08:14
Non-cutting time		00:18:15	00:07:13	00:04:07
Roughing time		01:11:06	01:21:31	01:21:31
Roughing time percentage		17.4%	28.9%	29.8%
Number of operations		8	9	8
Number of tool changing		7	2	4
Number of orientations		4 0°-140°-250°-180°	8 181°-271°-11°-91°-0°-140°-250°-180°	6 181°-271°-11°-91°-0°-180°
Part volume	mm^3	22732.11		
Stock volume		243575.38		
Machined volume		220453.57	220419.78	220419.90
Current part volume		23121.81	23155.60	23155.48
Excess volume		389.70	423.49	423.37
				

Moving to model 2, surprisingly, Table 7.5 shows that trial 2 gave a minimum machining time compared to trial 3. This contradicts simulation results obtained in chapter 6 where minimizing the finishing orientations managed to decrease machining time. However, further comparison shows that the cutting time difference between trial 2 and 3 is only about 4 minutes. Trial 3 performed cutting process with fewer orientations but it takes slightly more time to perform finishing operations. Remember this is just an estimated time and will probably be more or less in real machining conditions. As cutting time is highly dependent on part features, it is acceptable to find small deviations between the trials. After all, finishing using two orientations is still a reliable method to improve process efficiency. In the planning stage, it simplifies the classification of surfaces to be carried out within two orientations only. As mentioned in section 7.2.2, trial 1 used a smaller depth of cut (0.07mm instead of 1mm). Therefore, it is not comparable to other trials as a large amount of time is required to produce the part.

Table 7.5: Simulation results for model 2

Trials Criteria		Vehicle gear knob (Model 2)		
		Machining Trial 1	Machining Trial 2	Machining Trial 3
Machining time	hour:min:sec	08:21:43	05:17:32	05:21:53
Finishing time		07:12:56	04:05:58	04:12:06
Non-cutting time		00:15:46	00:05:08	00:03:37
Roughing time		00:53:02	01:06:26	01:06:10
Roughing time percentage		10.6%	20.9%	20.6%
Number of operations		6	8	6
Number of tool changing		5	2	1
Number of orientations		3 0°-120°-240°	7 180°-270°-10°-90°-0°-120°-240°	6 180°-270°-10°-90°-45°-225°
Part volume	mm^3	24965.52		
Stock volume		76272.48		
Machined volume		51168.80	51169.49	51168.96
Current part volume		25103.68	25102.99	25103.51
Excess volume		138.76	137.47	137.99
				

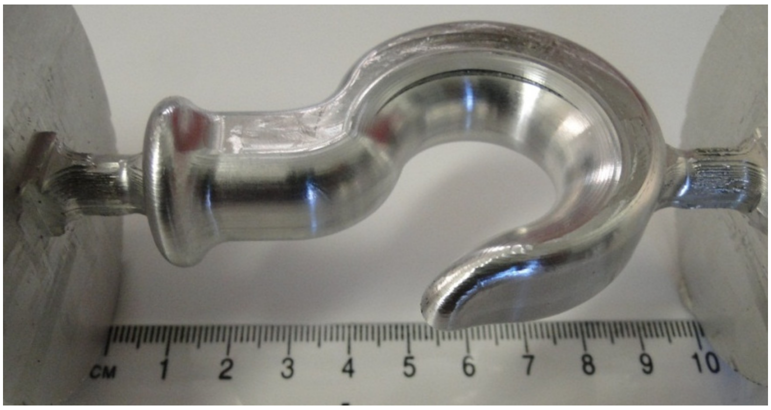
Meanwhile, excess volumes for trials 2 and 3 shared almost the same value of $137mm^3$. Similar to model 1, the distribution of excess material can be seen in the sacrificial support area and this influences the volume calculated. In the meantime, trial 1 indicates a similar excess volume of $138mm^3$ even though cutting occurred at a minimum depth of cut that caused machining time to be extended. This signifies the inefficiency of relying only on a flat end mill tool in finishing operations. It is expected that the stepping appearance on non-flat surfaces can still be seen and there is considerable amount of excess material left on the part. Essentially, the parts must be produced to verify the implications predicted from these simulation results.

7.3.2 Machining outcomes

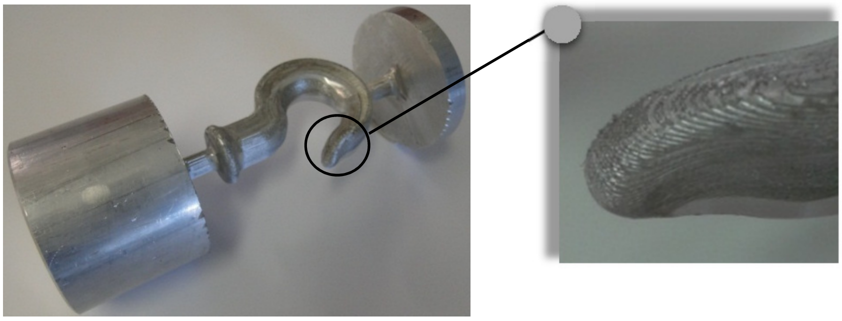
Machining experiments were carried out with the aim of verifying the approaches developed in this study. Previously, the simulation results have revealed several advantages brought about by implementing the suggested approaches. Machining trial 1 that replicates the original approach runs roughing and finishing operations within same cutting orientations. In order to simplify the planning task, finishing operations often employ small flat end mill tools to shape the model. It is undeniable that the method is capable of producing the parts but later issues emerge which reflect on part quality and cutting efficiency. Oppositely, the recently developed approaches implemented in this study manage to improve roughing operations by using different orientations sets. In addition to that, part quality is enhanced through the integration of tools in finishing operations. Analysing the machined parts will further confirm the improvements made from those approaches.

7.3.2.1 Visual inspections

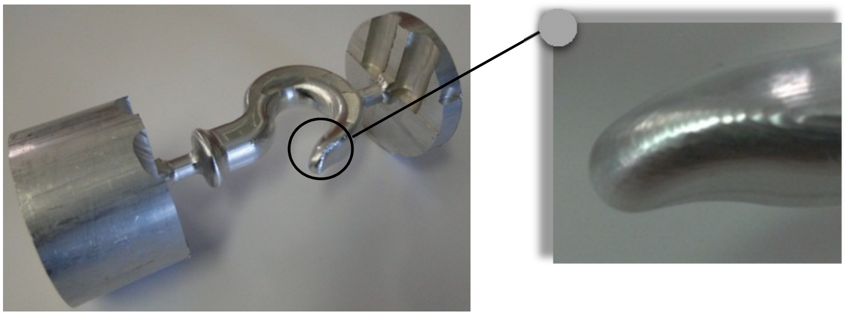
The results of machining experiments indicate the feasibility of implementing the developed approaches to enhance the rapid machining processes. Based on observations of the parts produced in trial 1, the staircase effect is clearly visible on non-flat surfaces. It has been suggested that the appearance can be reduced by cutting at a minimum layer thickness (Frank et al. 2004). Therefore, machining trial 1 for model 2 was executed with a minimum cutting depth. However, the layer effect still can be seen compared to the parts produced using multiple tools with larger cutting depths. Inspecting trials 2 and 3 is rather difficult as both adopted the same tooling approach in finishing operations. The differences rely only on the number of orientations and the cutting directions used. Therefore, further assessments are required to verify the surface quality. Figure 7.4 illustrates the quality of machined surfaces for each model and trial. After all, assigning tools to work on different part surfaces did enhance part appearance and quality. Moreover, the results can be improved further by modifying critical parameters in machining such as depth of cut, speeds and feeds as well as the number of finish passes. All these can be setup earlier and embedded inside the program to allow rapid process planning.



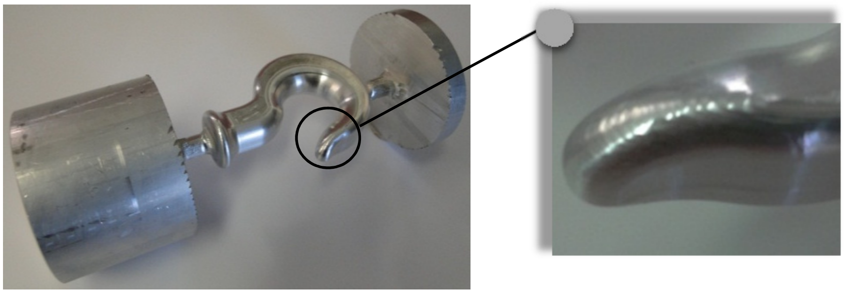
Crane hook model



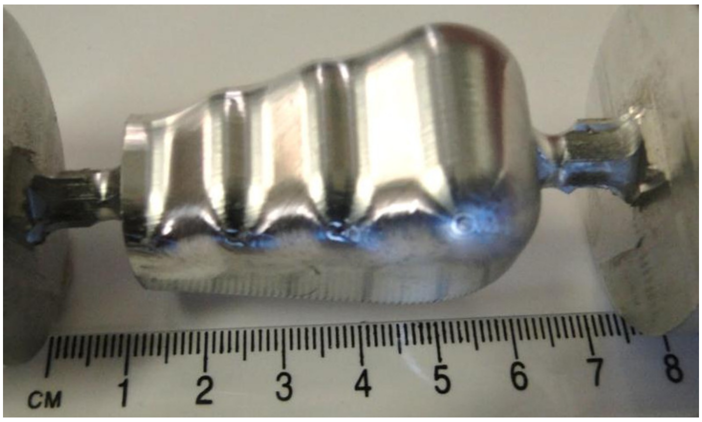
Machining trial 1: Machining with visibility orientations using single end mill tool



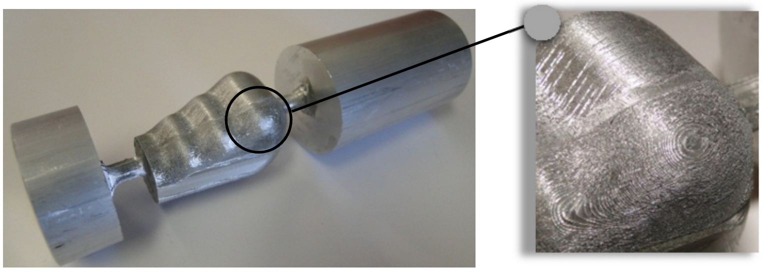
Machining trial 2: Machining with four roughing orientations using multiple tools



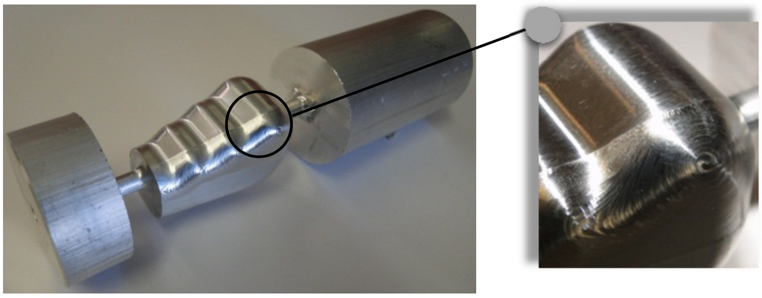
Machining trial 3: Machining with four roughing orientations, two finishing orientations and using multiple tools



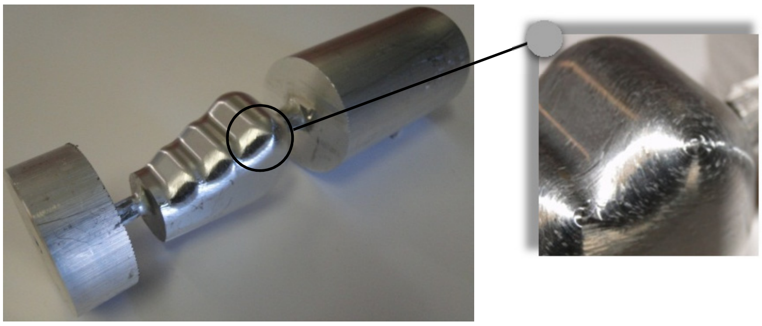
Vehicle gear knob model



Machining trial 1: Machining with visibility orientations using single end mill tool



Machining trial 2: Machining with four roughing orientations using multiple tools



Machining trial 3: Machining with four roughing orientations, two finishing orientations and using multiple tools

Figure 7.4: Machined parts (a) crane hook and (b) vehicle gear knob

In the other aspects, the approach suggested to execute roughing operations from an independent orientations set succeeded in reducing cutting times. As indicated by the data generated in the simulation analysis, the time spent on roughing operations did increase reasonably compared to the same operation in machining trial 1. As a result, finishing operations and total machining time reduced as recorded in trials 2 and 3. Figure 7.5 shows the material left on model 1 after completing roughing operations through four cutting directions. Besides, modification on the operations sequence had improved the overall efficiency of machining. Executing roughing operations at the initial stage of the process provided more flexibility in determining finishing orientations. In particular, orientations can be determined without any restriction arising from the need to avoid thin material formation. Parts with non-complex geometries can be machined with two orientations which indirectly simplified the planning tasks.

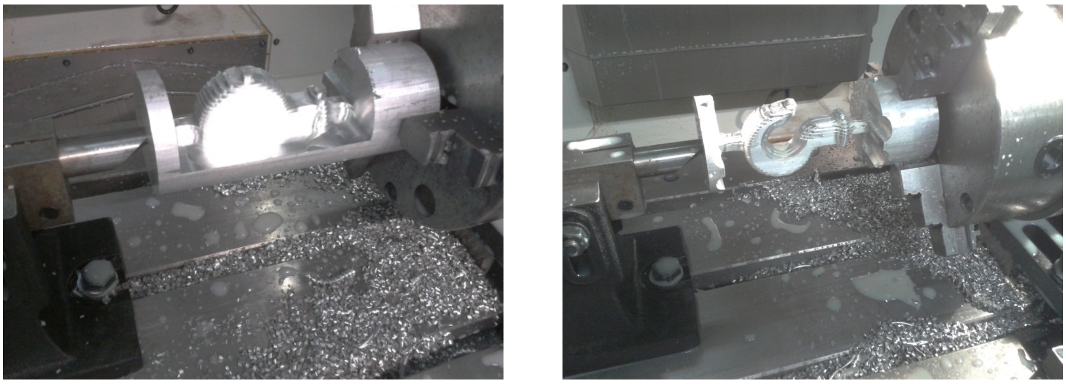


Figure 7.5: Roughing operations performed on crane hook model

In real machining processes, there are some variations between the times recorded on the machine and those from the simulation analysis. Table 7.6 compares the estimated and actual cutting times performed for each model based on different trials. It is apparent from this table that the variations ranged from 1 to 4% from the actual machining time. The main source for these variations is the manual adjustment of cutting feed during machining. At the planning stage, the operations used the same feed rates as cutting speed may vary based on tool size. In certain circumstances during machining, the feed rates were adjusted manually especially while engaging the cutting tool with the workpiece. The reason for this is to avoid sudden impact on the workpiece that may possibly break the cutting tool. Hence, some operations performed take a longer time to complete. Despite this, cutting data generated from simulation studies are still reliable to predict cutting time and roughly evaluate the efficiency of the operations.

Table 7.6: Comparison between estimation and real machining time

Time (hour:min:sec)	Estimated time	Actual time	Variations (%)
Model 1: crane hook			
Trial 1	06:48:30	07:02:17	3.3
Trial 2	04:41:06	04:48:24	2.9
Trial 3	04:33:52	04:36:59	1.1
Model 2: vehicle gear knob			
Trial 1	08:21:43	08:40:53	3.7
Trial 2	05:17:31	05:26:34	2.8
Trial 3	05:21:53	05:28:25	2.0

7.3.2.2 Roughness analysis

In order to verify the approach developed to improve finishing operations, measurements were taken from the part surfaces. It is widely recognized that surface roughness analysis is one of the techniques that can be used to determine the quality of machined parts (Ryu et al. 2006). In these experiments, roughness analyses were carried out on both models produced in trials 2 and 3. Since finishing operations are executed based on part surfaces, the measurements will be focused on these classified surfaces that reflect the type of tools used. Trial 1 is not included in this analysis. Based on the visual inspection, rough surfaces are clearly visible on machined parts due to the effect of using a flat end mill. Hence, the level of roughness can be predicted and it is not appropriate to compare it with trials 2 and 3.

The analysis was carried out by using a Form Talysurf PGI 1250A from Taylor Hobson. Similar to the measurements taken in section 3.3.2 surface roughness is calculated based on arithmetic mean average surface roughness (R_a). This parameter is widely used in most of the standards and thus allows direct comparison to verify the results. The flat surface can be measured directly by placing the part on the equipment table. However, in order to measure non-flat surfaces, a fixturing device is used to allow the part to be rotated to certain angles. This method reveals sufficient surfaces for measurement and ensures the stylus touches the part continuously. Later on, the results can be compared directly to the standards to identify the level of quality achieved. Measurements were taken based on direction of cutting tools moving downward to machine the parts. The range of the stylus movements are about 4 to 5 mm on part surfaces to take the measurements. The intention of the analysis is to portray the effects of using different tools based on classified surfaces. Thus, at least three measurements were taken on flat and non-flat surfaces which later suggests an average R_a for each region. Figure 7.6 shows exact locations where the stylus moved to calculate roughness and Table 7.7 sums up the average roughness values calculated.

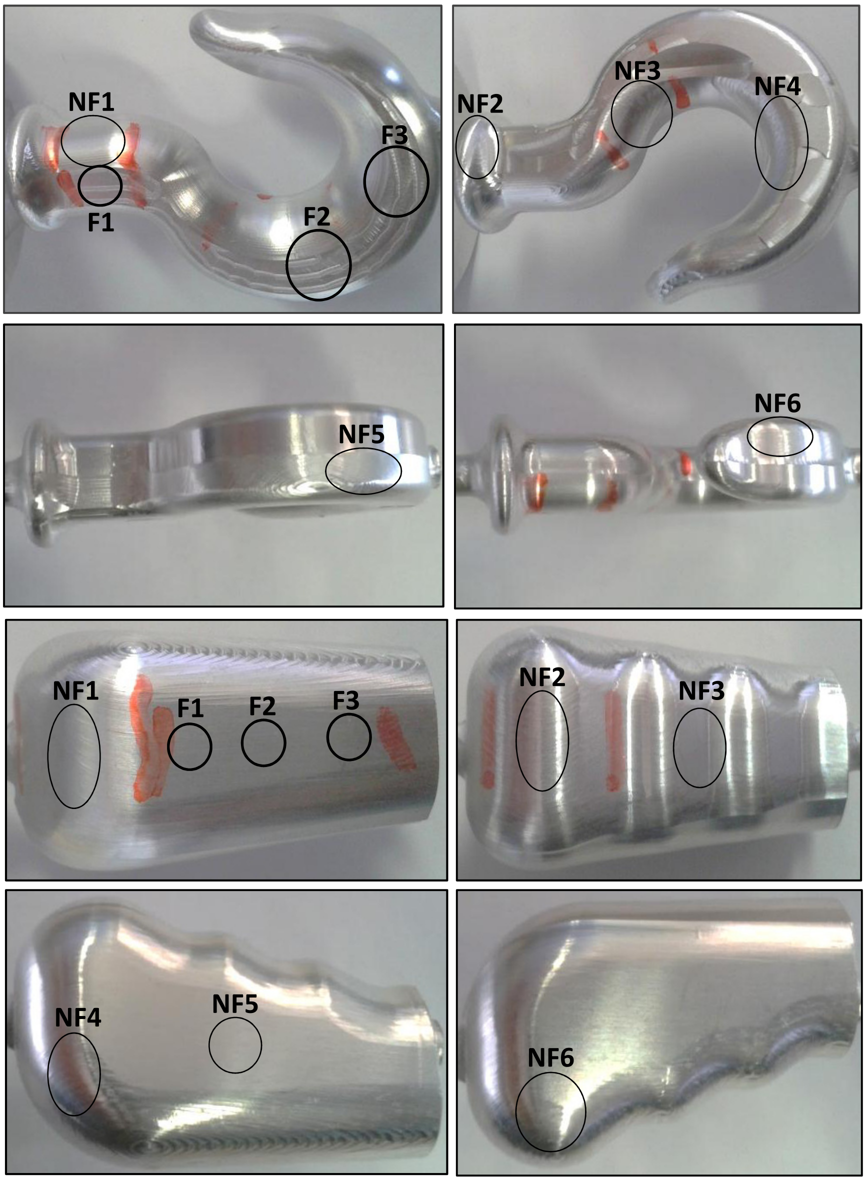


Figure 7.6: Measurements locations taken on the models

Table 7.7: Roughness measurement results

Model 1: crane hook						
Surfaces classification	Machining trial 2			Machining trial 3		
	Roughness value (µm) R_a		Average R_a	Roughness value (µm) R_a		Average R_a
Flat surface (F)	F1	0.1447	0.1880	F1	0.1739	0.1913
	F2	0.1245		F2	0.1639	
	F3	0.2949		F3	0.2362	
Non-flat surface (NF)	NF1	0.3477	0.4820	NF1	0.4816	0.4361
	NF2	0.5635		NF2	0.7274	
	NF3	0.3966		NF3	0.4498	
	NF4	0.5722		NF4	0.4866	
	NF5	0.3965		NF5	0.2528	
	NF6	0.6156		NF6	0.2188	

Model 2: vehicle gear knob						
Surfaces classification	Machining trial 2			Machining trial 3		
	Roughness value (µm) R_a		Average R_a	Roughness value (µm) R_a		Average R_a
Flat surface (F)	F1	0.1878	0.1568	F1	0.4905	0.5069
	F2	0.1978		F2	0.5101	
	F3	0.0847		F3	0.5200	
Non-flat surface (NF)	NF1	0.5166	0.4245	NF1	0.4651	0.4989
	NF2	0.4267		NF2	0.5347	
	NF3	0.2662		NF3	0.4970	
	NF4	0.4949		NF4	0.5370	
	NF5	0.2274		NF5	0.5040	
	NF6	0.6151		NF6	0.4560	

This table is quite revealing in several ways. First, the roughness values on flat surfaces are better compared to non-flat surfaces. This indicates the horizontal face on a flat end mill gives an advantage for the tool to get contact with the workpiece and remove material effectively. Second, ball nose end mills give slightly higher roughness values due to the scallop effect presented between each cutting level. But still, the tool is capable of shaping non-flat surfaces effectively compared to a flat end mill. Moreover, it would be possible to reduce roughness values by decreasing cutting depth but this would result in increased machining time. It is important to note that flat surfaces in machining trial 3 on model 2 are machined by using a ball nose end mill only. Due to the cutting directions used, the flat areas appeared as inclined surfaces which resulted in the use of a ball nose cutter. However, for the purposes of comparison, the measurements were still taken but the values are slightly higher reflecting the type of tool used. Finally, the overall roughness result has demonstrated that a certain level of quality has been achieved through the implementation of multiple tools in finishing operations.

Simulation studies in chapter 5 have set out the improvements gained by implementing different cutting tools in finishing operations. It is interesting to note that the roughness analyses conducted here have further confirmed the results produced in machining simulations. According to Baptista et al. (2000), surface roughness of around 1.0 µm is categorized as acceptable in finishing operations which require manual polishing whereas 0.5µm is equivalent to the roughness achieved in manual polishing. Referring to the data in Table 7.7, most of the average R_a value falls less than these ranges for both models. In comparison to the milling roughness standard (DeGarmo et al. 2003), the achieved roughness values are categorised as finer roughness for this particular method of manufacturing. It is undeniable that a flat end mill tool effectively produced the finest flat surface with a roughness value around 0.1 to 0.2 µm. Referring to BS ISO 1302(1992), these values fall within N3 and N4 roughness grade numbers which are equivalent to SPI B surface finish, mould roughness classification according to Society of the Plastic Industry (SPI). Under this category, the machined product can achieve typical surface requirements for plastic parts.

On the other hand, surfaces machined by a ball nose tool generated slightly higher roughness values but were still within an acceptable range. The values fall within N5 to N7 in roughness grade number and SPI C surface finish which implies semi-smooth polishing. In addition, these values are also within average achievable roughness for milling operations. Overall, the roughness results provide further support for the hypothesis that different cutters impart certain levels of quality to the part surfaces. Based on the comparisons made with roughness standards, it is clearly indicated that the machined parts managed to achieve satisfactory and reliable quality.

Several studies have investigated the roughness achieved by other RM processes. Common additive processes such as Stereolitography (SLA), Fused Deposition Modeling (FDM) and 3D printer have been used to produce tooling for sand and investment casting (Pal et al. 2007). On average the roughness achieved by these processes are between 2µm and 18µm. A review of laser additive manufacturing indicates roughness values around 9µm to 20µm based on deposition methods which include sintering, melting and cladding (Gu et al. 2012). Another study focused on optimizing control parameters in the Selective Laser Melting (SLM) process managed to achieve a minimum roughness value of 2.45µm (Król et al. 2013). Therefore, it can be concluded that the present results have revealed the potential of machining processes in RM applications. An approach to integrate flat and ball nose end mills in finishing operations is proven to enhance part quality. In fact, it satisfies the roughness requirement for finishing operations in milling processes and also achieves reliable quality in certain mould roughness standards.

7.3.3 Problems encountered in machining

Machining processes have been carried our using a Hurco 3-axis vertical CNC milling machine. Cutting operates according to the codes translated by the postprocessor in the NX software. In total, there were 6 parts machined (three parts produced for each model). The difference between each part for one model only relied on the approach used to machine the parts. As mentioned earlier, machining trial 1 utilizes the method adopted from original studies that initiated the use of CNC machines for the rapid application. On the other hand, the recently developed approaches in this study were implemented in machining trials 2 and 3. Both performed roughing operations using independent four orientations sets. Unlike trial 2, finishing orientations in trial 3 were minimized as both models possessed no intricate shapes on the part.

As expected, the machining experiments have revealed a few problems related to the set-up and simulation program used to create machining codes. One of the critical issues is with regard to roughing tool movement that overcuts the cylindrical workpiece at deep cutting levels. The side of the end mill cutter removes large amounts of material and the effect is shown in Figure 7.7. This problem is due to inaccurate toolpath planning where the cutting is not consistent between each level. In the worst scenario, it can lead to collision between the tool and the work holding device. Most of the cutting operations available in NX Manufacturing are suitable for processes that use ordinary clamping devices. However, in the rapid machining approach, an indexable device is used to clamp the cylindrical workpiece allowing rotation in one axis. This limits the tool movement. Thus, some modifications are required to the machining program at the planning stage.

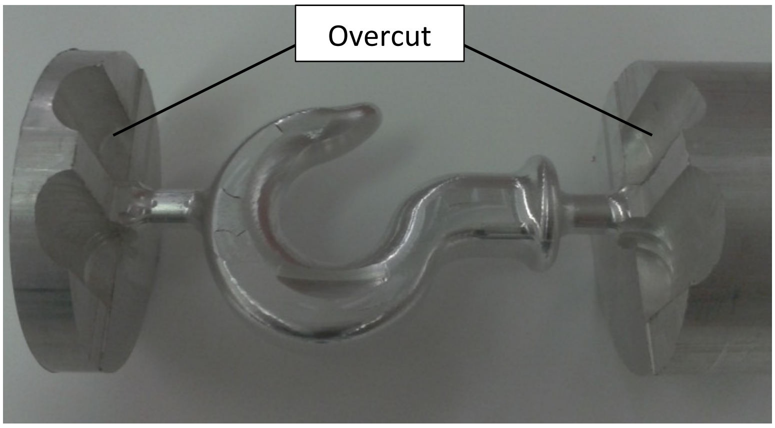


Figure 7.7: Cutting level problem that caused overcut to the workpiece

Presently, there are two solutions proposed to assist toolpath planning. First, two cylindrical blocks with the same diameter as the workpiece are created at both ends of the workpiece. There must be a gap between the workpiece and blocks which is equivalent to half of the roughing tool diameter. Later, these blocks are selected by a specific check function that ensures the tool x-y movements do not exceed these blocks. In the real situation, these blocks represent the indexable device that clamps the workpiece at both ends. Hence, cutting tools are restricted to move further from these blocks and prevent any collision with the clamping device. At the same time, it also ensures uniform cutting levels during roughing operations. This solution is already capable of preventing the overcut problem. However, it is worthwhile to improve cutting paths by guiding the tool engagement based on a plunging movement. In this way, cutting tools would approach the workpiece from the z direction before moving in the x and y axes to perform machining. This avoids the engagement from the x or y axis to cut the workpiece and thus prevents any possibility of a crash with the clamping device. Figure 7.8 illustrates the solutions suggested to assist toolpaths in machining. The creation of the check blocks and tool engagement direction can be performed automatically from the process planning programs. The method will be described further in chapter 8.

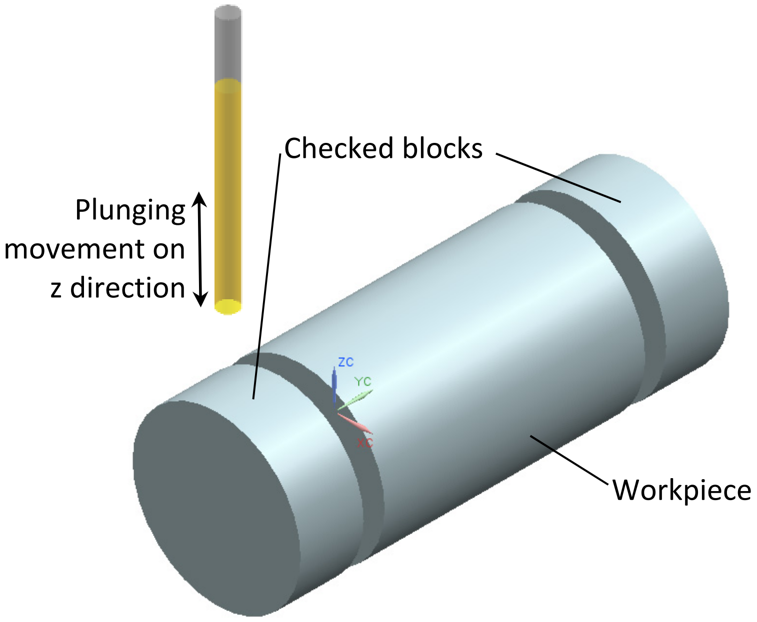


Figure 7.8: Overcut solutions

Other issues that arose from this experiment were related to defects present on the machined parts. Particularly in orientations where two cutting tools operated, cutting marks appeared on flat surfaces of the part. Reviewing the cutting simulation, it can be seen that these marks are present due to redundant cutting areas between the tools. During finishing operations, a flat end mill tool executes the first operations removing material on flat surfaces. Then, a ball nose cutter shapes non-flat surfaces on the part. However, in some isolated cases, this cutter will still move on flat surfaces even though the cutting area had already being defined earlier. It is most likely to happen if there is only a small area of flat surface presented in one cutting direction. Additionally, the plunging movement of the tool can cause cutter marks on flat surfaces. Due to the similar feed rates used for all movements, the cutting tool can get engaged too quickly from the z direction and cause the marks. Moreover, another defect can be observed around the area where two cutting orientations meet. Improper workpiece alignment with the clamping device is believed to cause cutting lines appearing in this area. All these defects are shown in Figure 7.9.

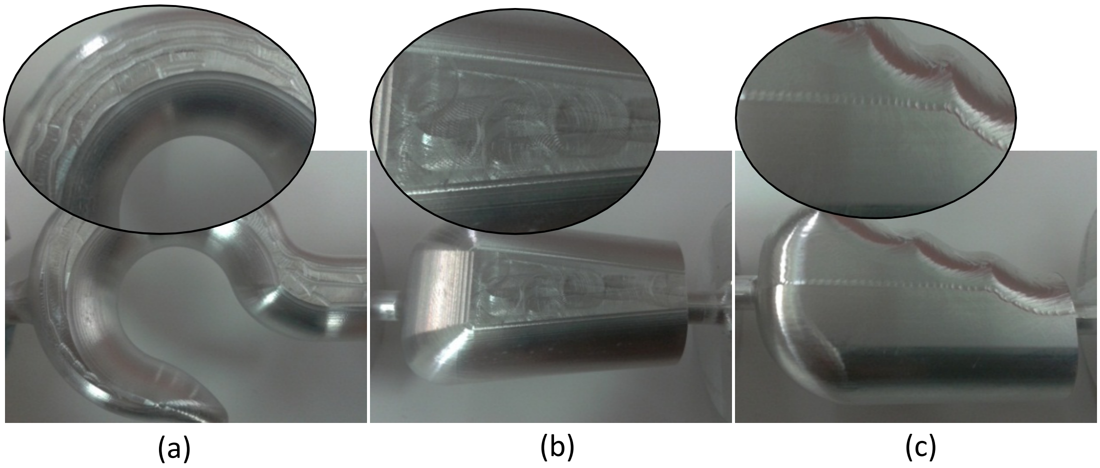


Figure 7.9: (a), (b) Cutter marks effect and (c) Cutting lines formation

The solutions are formulated by analysing the root cause of the defects presented. The first solution suggests that the cutting area between the tools must be identified properly. Only flat surfaces are selected while cutting with flat end mills and non-flat surfaces for a ball nose cutter. In order to secure these areas, a trim boundary option can be used on flat surfaces that have been cut earlier to prevent a ball nose cutter path intersecting with them. Meanwhile, cutter marks due to the plunging movement can be minimized by introducing another feed rate value for the z direction. This value should be lower than the standard value used for x and y movements. With this modification, the presence of round cutter marks on flat surfaces can be reduced. CNC-RM executes machining continuously without re-fixturing the workpiece between each orientation. Therefore, the indexable device needs accurate calibration during the installation on the machine table and also while clamping the workpiece. Taking this precaution can diminish the cutting line appearance on parts between the orientations.

7.4 Summary

The machining experiments conducted have illustrated the potential of the developed approaches in CNC-RM processes. Returning to the main objectives stated at the beginning of this chapter, it is now possible to state that the suggested approaches had been further verified and are ready for implementation. The results of these experiments show that roughing operations with a different orientations set is a reliable approach to optimise cutting processes. Furthermore, the analysis of the quality of machined parts has revealed the advantages of using different tools on flat and non-flat surfaces. However, there is some uncertainty in terms of machining time when finishing uses two cutting directions. This approach manages to simplify the planning tasks but the cutting time can be arguable and highly depends on part geometries. Indirectly, the experimental works became a platform to test customised programs created to assist in process planning. It works and fulfils the main purpose in assisting planning tasks but some modifications are required to tackle the problems encountered. Taken together the implementation of the developed approaches in rapid machining applications is strongly recommended.

CHAPTER 8

COMPUTER AIDED MANUFACTURING (CAM) FOR CNC-RM

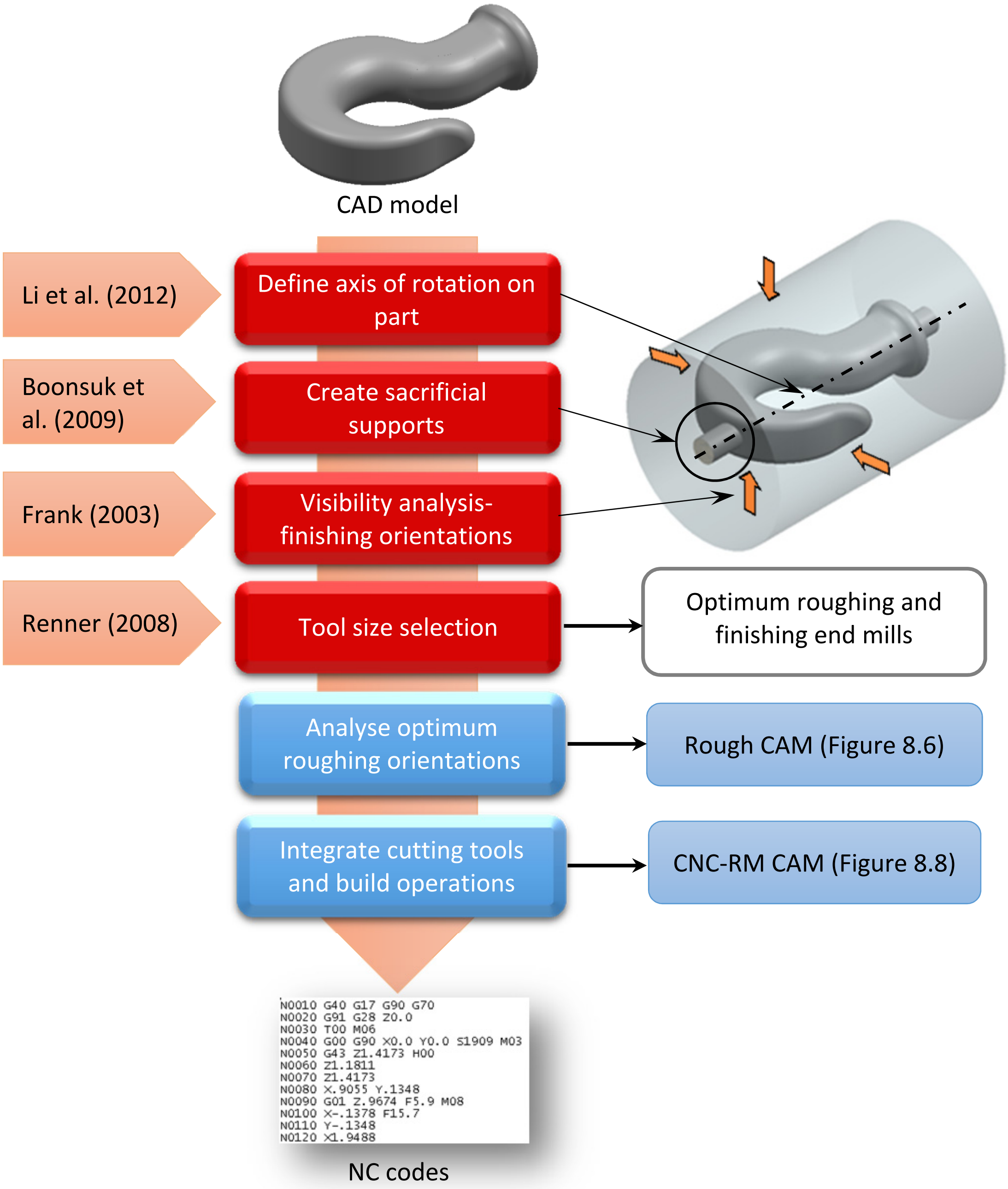
8.1 Introduction

Process planning is an important component of CNC machining, and plays a key role in RM processes. Despite the new approaches proposed to enhance machining efficiency, process planning remains as a crucial component to assist the implementations. In contradiction with other RM methods, process planning for CNC machining is highly dependent on the experience of the CAM operator or manufacturing experts (Relvas et al. 2004, Xu et al. 2011). This is the main obstacle that prohibits the application of machining in rapid processes. Generally, process planning for CNC machining involves substantial tasks and decisions to develop effective cutting operations. Several parameters need to be defined properly as well as cutting methods and the coordinate system on the machine. All these require considerable knowledge and experience to ensure that the machining program can be executed without failure and produce good products. Therefore, high quality machined parts can be achieved by implementing correct and reliable process steps in the planning phase (Zhao et al. 2011).

Recent developments in CAM technology have minimized the dependency on skilful machinists to handle machining process planning. Several attempts have been made to execute planning tasks for CNC machines in a semi or fully automatic manner (Frank 2007, Agrawal et al. 2013). Basically, the developments are carried out through a commercial CAD/CAM interface and are particularly used in the application of 3-axis milling with an indexing device. With few setups, the program will generate machining codes that assist cutting tools to machine from different orientations. Several main tasks are identified in the planning stage. Starting from a CAD model, the first step will be to define an appropriate axis of rotation for the part. This is followed by development of the coordinate system and the creation of sacrificial supports on the part. Then, visibility analysis is performed to identify the required cutting orientations which are important in ensuring that parts are completely machined. Finally, the roughing and finishing operations are generated based on the orientations proposed.

Substantially, a key aspect that allows the process to be automated is by constraining the planning problems (Bourne et al. 2011). As exemplified from previous developments, using standardized tool and cutting parameters, machining plans can be developed rapidly with minimum user interaction. The same planning program is applicable to parts that differ in terms of features and shapes. This is a core principle of developing automated process planning that allows CNC machines to work in RM environments. As a part of the automation requirement, this chapter will focus on process planning development particularly to fit the new approaches to established planning steps for rapid CNC machining. Basically, there are two main approaches developed to enhance machining for RM. The first proposal suggests the separation of the orientations sets for roughing and finishing. These operations are executed at the beginning of machining processes through four standard cutting directions. In order to determine an optimum roughing orientations set, cutting simulations are performed that cover all possible angles. Orientations with minimum machining time are denoted as optimum cutting directions. Therefore, the first program is developed to find an optimum orientations set for roughing operations. This information is then used by the second program that constructs machining operations for the CNC machine. In addition, this program also permits the use of different types of cutting tools in finishing operations that are based on part surfaces. Generally, the frameworks of both programs are quite similar because they employ the same cutting operations and process sequences.

However, the first program particularly works to simulate the operations and records machining times for the purpose of comparison. In contrast, the second program is particularly used to create machining operations to run on the CNC machine. Figure 8.1 shows where the current developments fit into previously established tools in process planning. The last step of conventional process planning is replaced by the new approaches developed in this study.



```
N0010 G40 G17 G90 G70
N0020 G91 G28 Z0.0
N0030 T00 M06
N0040 G00 G90 X0.0 Y0.0 S1909 M03
N0050 G43 Z1.4173 H00
N0060 Z1.1811
N0070 Z1.4173
N0080 X.9055 Y.1348
N0090 G01 Z.9674 F5.9 M08
N0100 X-.1378 F15.7
N0110 Y-.1348
N0120 X1.9488
```

Figure 8.1: New approaches in CNC-RM process planning

8.2 Fundamental development of machining operations

Primarily, there are two main cutting operations executed in CNC-RM processes. These operations are repeated in different cutting directions that represent the orientations used to machine the parts. As described in section 4.2.3, rest milling in the NX manufacturing application has been selected to develop roughing and finishing operations. The instructions to construct both operations are quite similar and the differences only relate to tool sizes and a few cutting parameters. Detailed instructions will be discussed further in this section which represents a core element that works behind the program developed for planning process. Basically, the development of cutting operations can be viewed in two levels of instructions as shown on Figure 8.2. The first level consists of primary instructions that need to be developed before creating the operations. Then, the next level gathers the steps taken to build cutting operations in one particular orientation. At the preparation level, a few one-off tasks are performed before developing a series of machining operations. These include selection of the part and blank and also the creation of appropriate cutting tools that will be used in the operations. To comply with these setups, a CAD part model must already exist complete with sacrificial supports and cylindrical blank that represents the workpiece. Later, the program developed will assist in the determination of these parameters according to this initial specification. Tools of the right sizes and dimensions are created to be identical with the tools used in the CNC machine. This will assist the simulations to run accurately based on real machining operations.

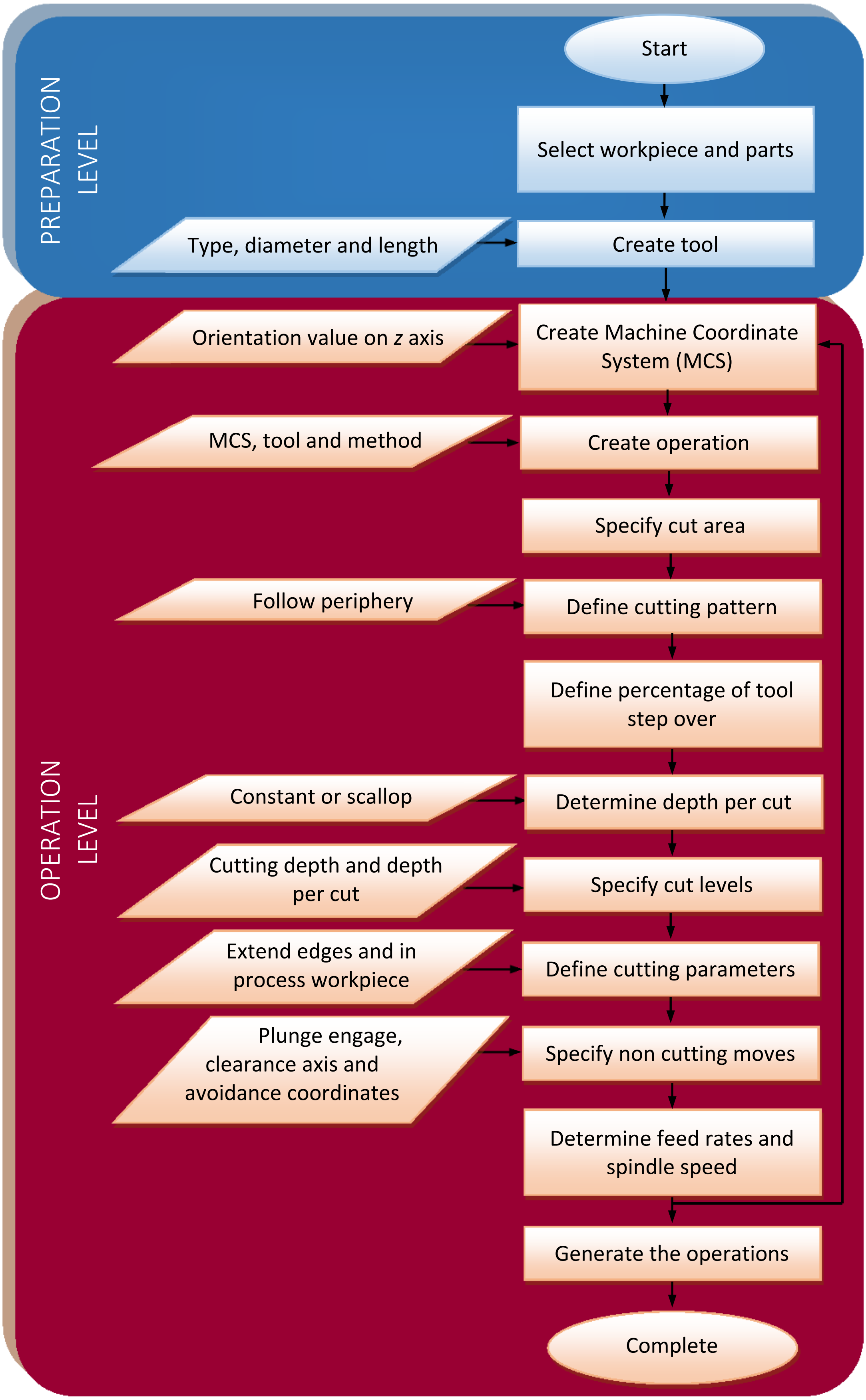


Figure 8.2: Instructions used to create the rest milling operation

Turning now to the operational level, numerous tasks are carried out to construct the machining operations consisting of rough and finish cuts. Initially, a machining coordinate system is created which represents the cutting orientations that will be used. Depending on the part surfaces, there might be one or two operations contained in one orientation. In order to standardize the process planning, only one cutting operation is used even though the NX software is equipped with various cutting types for different applications. There are no cutting operations developed particularly for the CNC-RM application, but, after considering the requirements of the process, rest milling is the most favourable operation. It conserves some flexibility allowing customisation and possesses an in-process workpiece function. Without any knowledge from previous cutting orientations, machining operations tend to generate inefficient long toolpaths and redundant cutting areas (Petrzelka 2009). The IPW function eliminates this problem because it capable of identifying material remaining after previous operations during current cutting processes. Therefore, the rest milling operation is suitable for machining processes that execute cutting through several orientations without re-fixturing the workpiece.

A cutting area command is used to specify the regions where the machining is going to be performed on the part. All areas are considered as cutting regions except for the areas that connect sacrificial supports to the cylindrical block. The cutting tool follows the peripheral pattern of the part and removes material layer by layer uniformly until a predetermined cutting depth is reached. Next, the tool step over is identified based on the type of machining operation. This guides the distance of cutting tool movement to start new cutting passes within the same machining level. The next operation setup is related to the cutting levels. There are two parameters defined in this setup which are cutting depth and depth per cut. Based on the tools adopted, cutting depth is usually defined to the centre of the cylindrical workpiece only and depth per cut is dependent on the type of operation and tool diameter. Following this, the ranges of the cutting region are defined and the in-process workpiece function is activated. Now, in the non-cutting moves task, the engagement is defined based on plunging movement where the tool starts cutting from the z-axis. Additionally, the clearance axis and avoidance coordinates are defined to be at least 10mm away from the workpiece and aim to prevent any possible collision in the machining area.

Finally, the last task for creating a cutting operation is to determine the cutting parameters. These values are influenced by the workpiece material and cutting tool sizes. All the steps described at the operational level are repeated to create machining operations for other orientations. The complete machining program requires the generation of several cutting orientations and operations. If a single cutting tool were used, seven cutting orientations need seven machining operations to complete one machining program. This reflects the massive amount of repetitive tasks involved if the program is constructed manually. Therefore, a practical and reliable method is required to handle the process planning tasks. Generally, the tasks described in this section are applicable for both roughing and finishing operations. However, some cutting parameters are setup differently between the operations. For example, the finishing operation employs a smaller depth of cut compared to the roughing operations. At the moment, the program developed to execute the planning tasks in this study is only suitable for aluminium parts. This specification constrains some of the cutting parameters and allows them to be embedded inside the program. Therefore, only a few setups are required before the program constructs the operations and produces machining codes for CNC machines. Table 8.1 summarizes the cutting parameters built-in the program for roughing and finishing operations.

Table 8.1: Cutting parameters embedded inside the programs

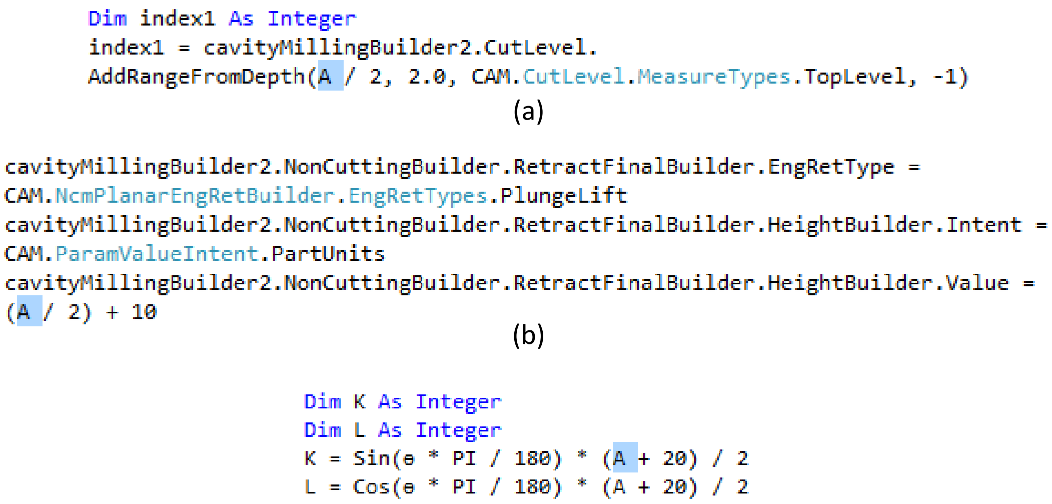
Machining parameters	Roughing operation		Finishing operation	
Horizontal feed rates	400 millimetres per minute (mmpm)			
Vertical feed rates	150 millimetres per minute (mmpm)			
Safety distance (mm)	D/2 + 10		D/2 + 5	
Cutting levels (mm) D=workpiece diameter Ftool=finishing tool diameter	D/2		Flat end mill	Ball nose end mill
			D/2	D/2 + Ftool/2 +0.5
Tool size (mm)	Cutting speeds (rpm)	Depth of cuts (mm)	Cutting speeds (rpm)	Depth of cuts (mm)
3	NIL	NIL	6366	0.1
4	NIL	NIL	4774	0.2
5	3819	0.5	3819	0.2
6	3183	0.8	3183	0.2
7	2728	0.8	2728	0.3
8	2387	1.0	2387	0.3
9	2122	1.5	2122	0.4
10	1909	1.5	1909	0.4
11	1736	2.0	NIL	NIL
12	1591	2.0	NIL	NIL

8.2.1 Customisation of programming codes

The NX open API (Application Programming Interface) allows changes and customisation of NX instructions without manually running the applications in the interface. “Open API is a collection of routines that allows programs to access and affect the NX Object Model” (Siemens PLM. 2009). This application permits users to access the codes behind NX in executing certain operations. There are several ways to utilize this tool. Since CNC-RM is a customised machining method, the journaling application is a suitable way to develop the program for process planning. Basically, this application is capable of recording, editing and replaying NX sessions in executing certain tasks. It translates the instructions into a script file based on a common programming language. In this study Visual Basic has been used to develop machining programs. In order to understand the relationship between the instructions and recorded codes, simple actions can be performed in NX while activating the journaling tools (Moi 2013).

Therefore, each of the tasks at the preparation and operation levels is performed manually and is recorded through journaling. Then, a review process is conducted to identify which part of the code reflects the input given by the user. Now, the codes are modified or replaced to meet the process requirements. These are the general processes performed to develop the programs in the machining planning stage. There are two methods adopted in modifying the codes recorded from journaling. As most of the operations are performed repeatedly, some of the tasks can be grouped together and run by using same data input. The second method works on removing the codes stickiness so that it can be applicable to any components or CAD models. Usually, original recorded codes are highly dependent on specific features of the part currently being processed. This cause a stickiness where the codes are not able to process other parts with different features. Therefore, removing the stickiness will make the codes universal and applicable to different models.

In order to simplify the input parameters, several tasks that have correlation between each other are linked together using the same variable. Thus, one parameter keyed in the program can be used by many tasks to perform desired functions. For example, the value of the workpiece diameter will be useful for several other tasks such as determining cutting depth, plunging height and avoidance coordinates. The same goes for the tool diameter where the value will determine the machining depth of cut and cutting speed. In the program, workpiece diameter is represented as variable ‘A’. Figure 8.3 shows the particular codes that utilize this value to formulate other cutting parameters. Having this modification, the input parameters are not only assigned to one specific task but are also shared with other tasks to generate operations efficiently. Therefore, finding common inputs between the tasks minimizes the parameters require from the user.



```
Dim index1 As Integer
index1 = cavityMillingBuilder2.CutLevel.
AddRangeFromDepth(A / 2, 2.0, CAM.CutLevel.MeasureTypes.TopLevel, -1)
```

(a)

```
cavityMillingBuilder2.NonCuttingBuilder.RetractFinalBuilder.EngRetType =
CAM.NcmPlanarEngRetBuilder.EngRetTypes.PlungeLift
cavityMillingBuilder2.NonCuttingBuilder.RetractFinalBuilder.HeightBuilder.Intent =
CAM.ParamValueIntent.PartUnits
cavityMillingBuilder2.NonCuttingBuilder.RetractFinalBuilder.HeightBuilder.Value =
(A / 2) + 10
```

(b)

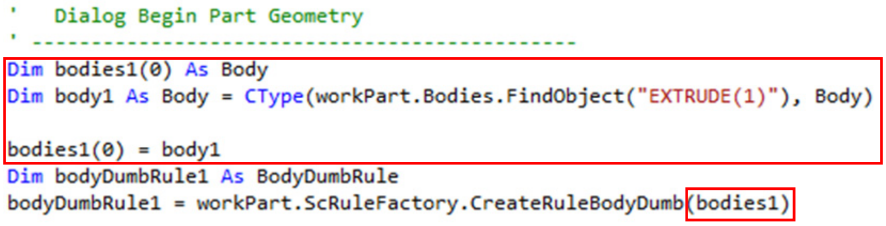
```
Dim K As Integer
Dim L As Integer
K = Sin(θ * PI / 180) * (A + 20) / 2
L = Cos(θ * PI / 180) * (A + 20) / 2
```

(c)

Figure 8.3: (a) Cutting depth, (b) Plunging height, (c) avoidance codes

Meanwhile, the second method is quite challenging because it involves eliminating a portion of the original codes and replacing it with modified codes. Initially, the codes produced are only capable of working on a particular part with specific features and geometries. These codes are used to identify the workpiece and part during the preparation level in process planning. The original codes clearly indicate the body representation as EXTRUDE(1) which defines the part. However, if this code is run on other CAD models, the body representation might be different and potentially cause an error in the program. In order to remove the stickiness, these codes are replaced with other codes that are applicable to any part.

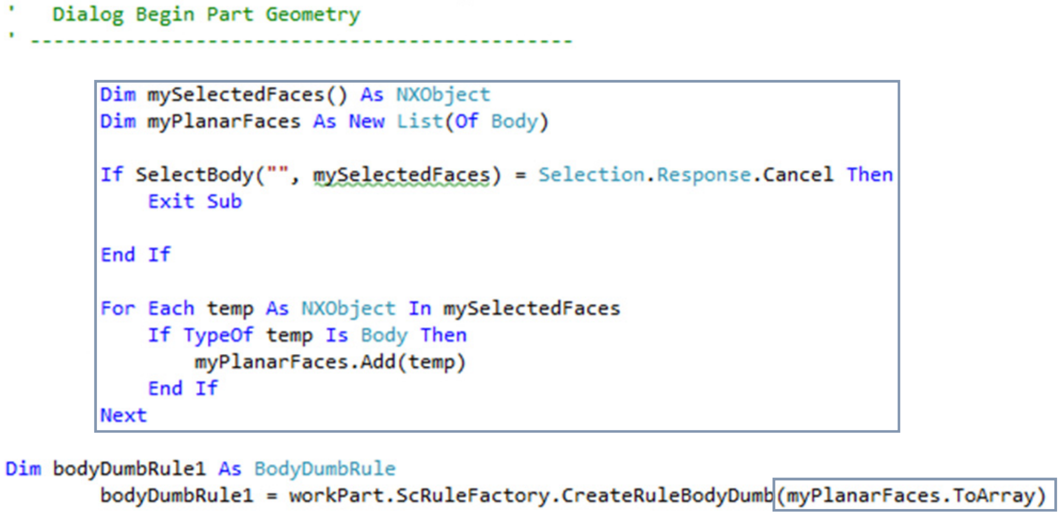
Instead of referring to specific part features, the new codes will pop out the selection window and allow the user to select the part body directly. This modification grants adaptability for the codes to process any parts while at the same time conserves some flexibility in the program. The same modification is also adopted when specifying the cutting area on parts. The functional codes that worked behind the selection window are given in Appendices C and D which represent the selection of body and cutting areas. Consequently, having functional codes embedded in the program succeed in removing the stickiness and expanding the application to various parts. A piece of code presented in Figure 8.4 shows an example of the original codes being replaced with new functional codes.



```
'   Dialog Begin Part Geometry
' ---------------------------------------------
Dim bodies1(0) As Body
Dim body1 As Body = CType(workPart.Bodies.FindObject("EXTRUDE(1)"), Body)

bodies1(0) = body1
Dim bodyDumbRule1 As BodyDumbRule
bodyDumbRule1 = workPart.ScRuleFactory.CreateRuleBodyDumb(bodies1)
```

Original codes



```
'   Dialog Begin Part Geometry
' ---------------------------------------------

      Dim mySelectedFaces() As NXObject
      Dim myPlanarFaces As New List(Of Body)

      If SelectBody("", mySelectedFaces) = Selection.Response.Cancel Then
          Exit Sub

      End If

      For Each temp As NXObject In mySelectedFaces
          If TypeOf temp Is Body Then
              myPlanarFaces.Add(temp)
          End If
      Next

Dim bodyDumbRule1 As BodyDumbRule
      bodyDumbRule1 = workPart.ScRuleFactory.CreateRuleBodyDumb(myPlanarFaces.ToArray)
```

Modified codes

Figure 8.4: Original codes replaced with new functional codes

In this study, two programs were developed to assist the planning stage. The first program (Rough CAM) was created to run a series of machining simulations virtually and to record estimated cutting times which are subsequently used to propose an optimum roughing orientations set for the analysed part. The second program (CNC-RM CAM) was developed to cater for cutting tools integration and to produce machining codes to run the CNC machine. It needs an output from the first program to generate the cutting operations effectively. With necessary inputs, these programs are capable of rapidly generating machining operations and thus minimize the complexity of planning tasks.

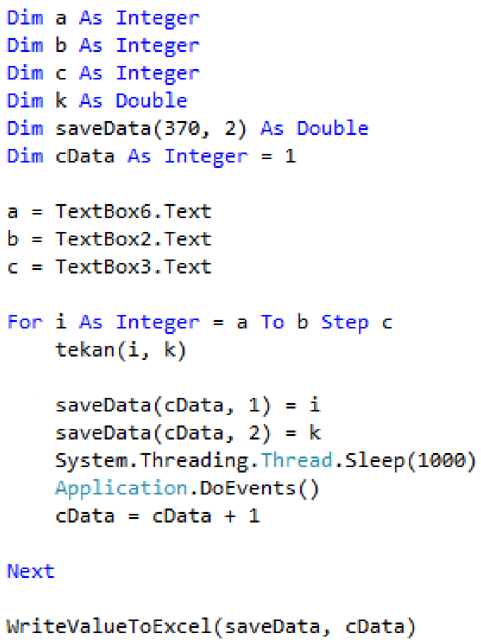
8.3 CAM for rough cutting orientations

The main purpose of the Rough CAM program is to perform the machining simulations from a range of cutting directions. At the end of the simulations, estimated cutting times based on cutting direction are produced and orientations with minimum times are selected. First, the program constructs roughing and finishing operations required to completely machine the part. These operations utilize only flat end mill tools with different sizes. Finishing orientations are based on angles defined in the program input. By default, the first series of roughing operations are generated at 0^{o}-90^{o}-190^{o}-270^{o} cutting orientations. Then, the program works by changing the orientation values automatically, to simulate the operations and record machining times. These processes are repeated until all possible cutting directions have been analysed and, finally, excel data is produced. Cutting time information can be easily sorted to identify which orientation possesses the minimum time.

8.3.1 Journaling and modifications

The journaling tool records different machining operations based on the number of finishing orientations. In this program, there are selections of 2, 3 or 4 finishing cutting directions. Modifications described in section 8.2.1 are conducted on the codes containing instructions to create the machining operations. Several parameters that need to be used as program inputs are defined. Among these parameters are workpiece diameter, finishing orientation values, roughing and finishing tool diameters, orientation ranges and step value. There are two important modifications required for the programming codes. The first one is to instruct the simulation to run continuously based on different roughing orientation values. Hence, the program will run the simulations according to the roughing orientation ranges that probably lie between 0^{o} and 360^{o} for one complete analysis. If the part possesses an axis symmetrical shape, then the possible cutting ranges could be less. Therefore, there are input sections provided in the program interface to allow user to key in necessary values for the simulations.

The step value is provided to minimize the coverage directions. Instead of moving only 1^{o} between each simulation, the value can be changed to 5^{o}, 10^{o} or any suitable step angle that the user requires. Increasing the step value will minimize the simulation time as only few cycles are required to produce the results. As a consequence, the orientation proposed is not considered to be an optimum because the analysis did not cover all possible directions. However, this method provides reliable orientations for roughing operations. Figure 8.5 illustrates the codes used to simulate roughing operations based on input orientation ranges. Based on the codes, analysis starts from the first orientation denoted as ‘a’ until the last orientation represented as ‘b’ and ‘c’ is a step value. All these are defined through the textboxes provided which are linked to the variables.



```
Dim a As Integer
Dim b As Integer
Dim c As Integer
Dim k As Double
Dim saveData(370, 2) As Double
Dim cData As Integer = 1

a = TextBox6.Text
b = TextBox2.Text
c = TextBox3.Text

For i As Integer = a To b Step c
    tekan(i, k)

    saveData(cData, 1) = i
    saveData(cData, 2) = k
    System.Threading.Thread.Sleep(1000)
    Application.DoEvents()
    cData = cData + 1

Next

WriteValueToExcel(saveData, cData)
```

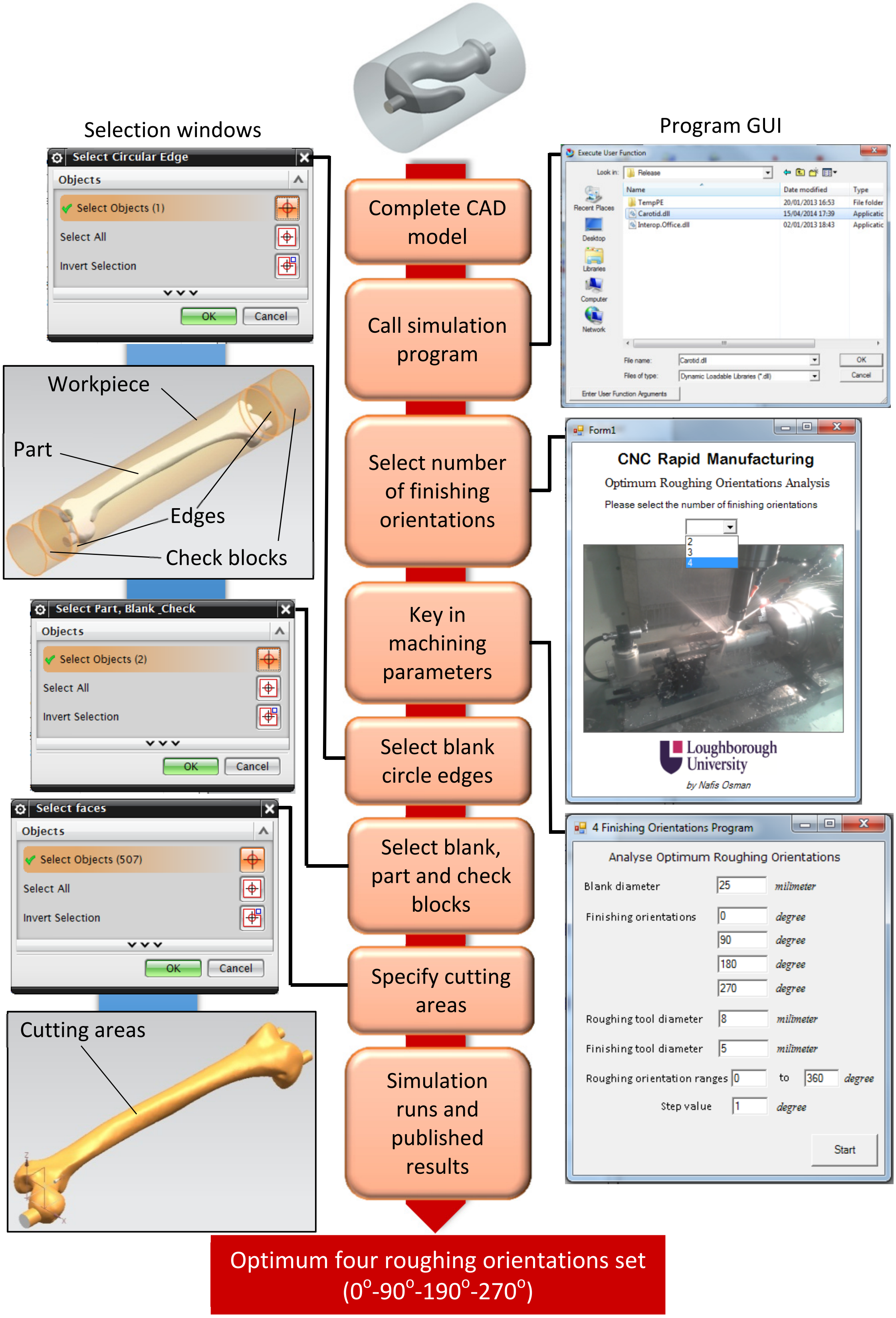
Figure 8.5: Instruction to repeat the simulation

The second modification requires the programming codes to be equipped with the instructions to record cutting time within each orientation and later produce the data in excel format once the simulations are complete. These instructions are achieved by using two functional codes embedded at the end of the program instructions. The first code extracts the total machining time value indicated on the operational navigator of the NX interface. Meanwhile, the second code is particularly used to organize and export all the data into excel format after the analysis cycle is complete. These codes are shown in Appendix E. All modifications support the program in searching for optimum roughing orientations and running the simulations successfully.

8.3.2 Procedures and Graphical User Interface (GUI)

Rough CAM is used to find optimum roughing orientations and to compile all machining operations required. The complete machining operations are developed first before the program simulates the operations based on roughing orientations values and records the cutting times. Initially, CAD models are prepared completely including sacrificial supports and blanks. Then, Rough CAM is called from a predetermined file location. Once activated, the first GUI window provides a selection of a number of finishing orientations that are required to machine the part. Next, a machining input window appears and the user needs to key in the simulation parameters. There are six items of machining information required: blank diameter, finishing orientations, roughing and finishing tool sizes, orientation ranges and step value. This is the final GUI built to run the simulation analyses. Figure 8.6 summarizes the process flow in roughing orientations analyses.

When the program begins to construct the machining operations, selection windows will appear to assist the user in specifying several other parameters. Circular edges on both ends of the workpiece are selected to create the check blocks. As discussed in section 7.3.3, these blocks are used to limit the tool movement and eliminate any possibility of collision with the indexer. After this, the user needs to define part, workpiece and check blocks through a series of selection windows. Finally, cutting areas are specified which cover all part and sacrificial support surfaces. However, the vertical faces of sacrificial supports must be left unselected so that they remain connected to the workpiece until machining has been completed. The simulations will keep running until all the cutting orientations are analysed. The results containing roughing orientations and machining times are then output in excel format. The user can manipulate the data easily to search for an optimum orientations set.



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Interop.Office.dll	02/01/2013 18:43	Applicatic

File name: Carotid.dll
Files of type: Dynamic Loadable Libraries (*.dll)

CNC Rapid Manufacturing

Optimum Roughing Orientations Analysis

Please select the number of finishing orientations

2
3
4

Analyse Optimum Roughing Orientations

Blank diameter 25 milimeter
Finishing orientations 0 degree
90 degree
180 degree
270 degree
Roughing tool diameter 8 milimeter
Finishing tool diameter 5 milimeter
Roughing orientation ranges 0 to 360 degree
Step value 1 degree

Figure 8.6: Process planning flow for optimum roughing orientations

8.4 CAM for tools integration and generation of machining codes

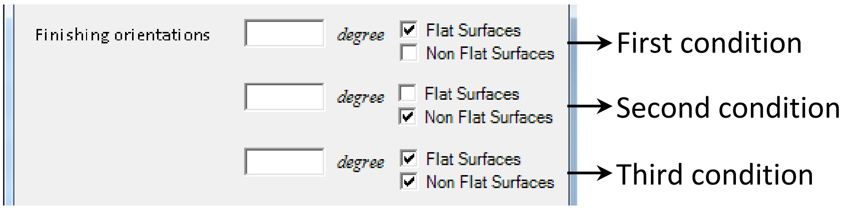
This section describes a CNC-RM CAM program that is intended to perform real process planning for CNC-RM. Unlike Rough CAM that was used for analysis purposes, CNC-RM CAM developed here creates machining operations and translates the processes based on a specific postprocessor. An optimum orientations set proposed by the analyses is used to generate roughing operations. In the same way as Rough CAM, finishing operations are executed at the orientations suggested by visibility analysis. But a main difference can be seen in the cutting tools used in the operations. Based on recent improvements in tool selection, finishing operations are performed by adopting different cutting tools based on the type of surfaces present on the part. In order to assist the selection, CNC-RM CAM interacts with the user to define suitable cutting areas for different end mills. Hence, up to two finishing operations are possibly performed in one cutting orientation.

It is important to note that the user is expected to make several cutting area selections in order to assign the cutting tools accurately. The classification of surfaces is totally dependent on cutting directions. Any surfaces that are perpendicular to the cutting tool are defined as flat surfaces and the rest of the surfaces are considered as non-flat. This basic guideline needs to be understood by the user while selecting the cutting areas on the part. Following this, a series of machining operations are constructed to fabricate particular parts. Once completed, the operations can be validated within the NX interface. Finally, machine codes are generated and transferred to the CNC machine to perform cutting processes.

8.4.1 Journaling and modifications

Basically, the CNC-RM CAM program is quite similar to Rough CAM in terms of the structure and the process sequence. However, the challenge would be in sorting the codes for finishing operations that need to execute numerous selection instructions. At first, using one CAD model as an example, journaling records are created for all processes including roughing and finishing operations to machine the part. The model must contain flat and non-flat surfaces at each finishing orientation. Therefore, two machining operations are created that utilize flat and ball nose cutters. At the end of the recording, one complete machining program is generated. Then, the modifications are carried out on the programming codes to remove the stickiness and assign common variables. These enhance the adaptability of the program to process different part shapes and features. Particular attention is required in organizing the cutting area selections during finishing processes. The user needs to define surfaces on the part and assign suitable cutting tools to execute the finishing operations. Therefore, additional codes are required for each finishing orientation to assist the selection of flat and non-flat surfaces. These functional codes are illustrated in Appendix F.

In CNC-RM process planning, there are three possible cutting conditions that could be found in one finishing orientation. First, only flat surfaces on the part which require one cutting operation using a flat end mill. Second, only non-flat surfaces identified within the cutting direction. Hence, one finishing operation is created by using a ball nose end mill. Lastly, the third condition occurs when both surface types are present, and will result in two finishing operations. To cater for these three conditions, there are checkboxes provided in the program interface to trigger the operations that need to be executed in machining. Figure 8.7 shows a part of the program GUI that contains several checkboxes which represent the two surfaces on the part in one finishing orientation. The tick checkboxes will activate the particular codes to create the operations and display the required selection window. Therefore, unnecessary operations can be avoided while dealing with various kinds of machined parts. Eventually, this program effectively and rapidly creates machining operations, while at the same time it is capable of integrating different cutting tools and achieving a reliable quality standard.



Finishing orientations

degree ☑ Flat Surfaces ☐ Non Flat Surfaces

degree ☐ Flat Surfaces ☑ Non Flat Surfaces

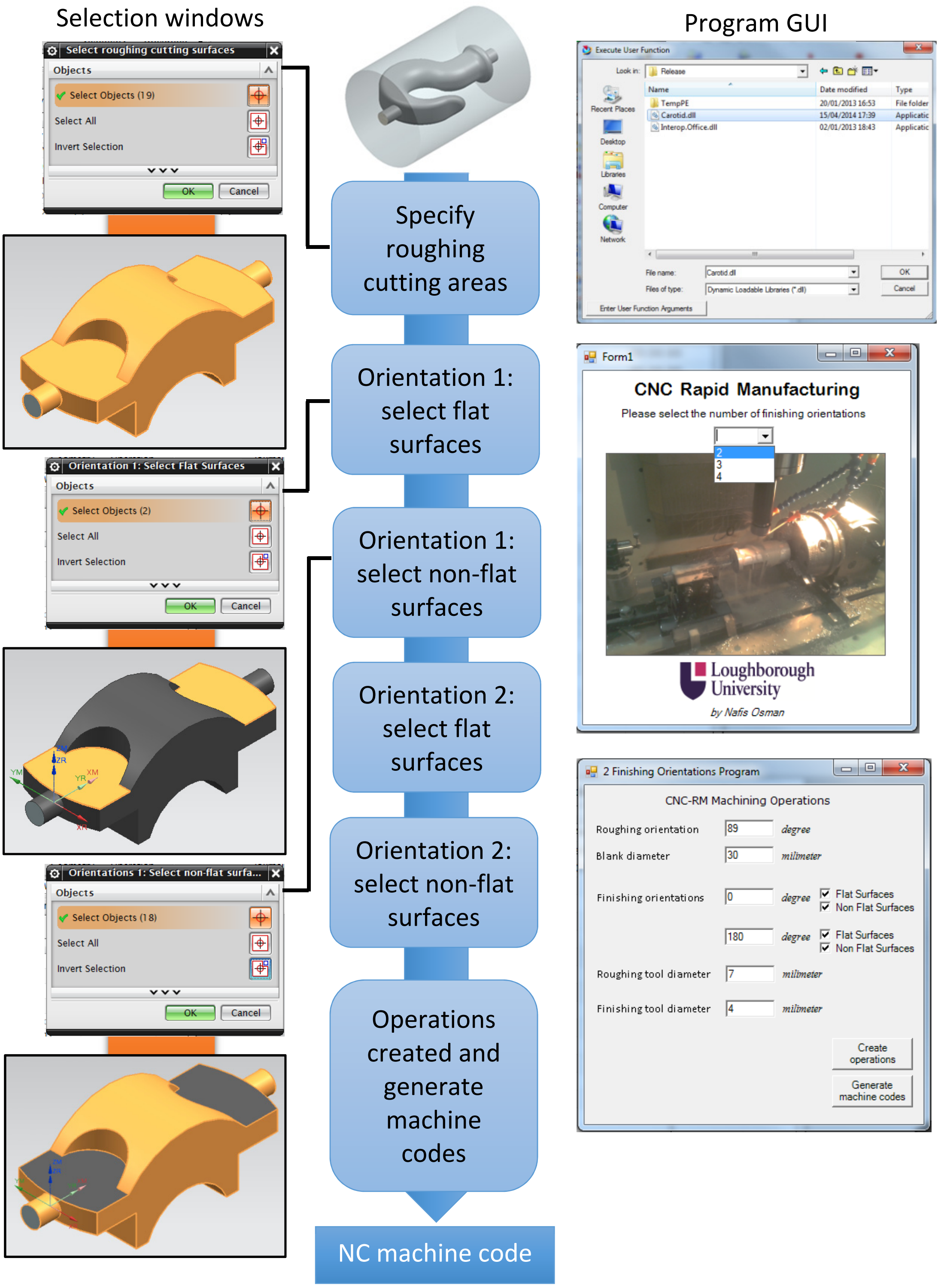
degree ☑ Flat Surfaces ☑ Non Flat Surfaces

Figure 8.7: Surface classification selection in finishing operations

8.4.2 Procedures and Graphical User Interface (GUI)

A customised program has been developed that is capable of building the machining operations for various cutting orientations. Once CNC-RM CAM is called, the first GUI allows the user to determine the number of finishing orientations for the part which is similar to Rough CAM described in section 8.3. Then, a second GUI appears and machining parameters need to be inserted. The first information request is for the optimum roughing orientation value proposed from Rough CAM. Only one angle is needed as the remaining three roughing orientations will be generated accordingly as setup inside the program. Next, other inputs are recorded including blank diameter, finishing orientations and cutting tool diameters. The aforementioned guideline in section 8.4.1 needs to be implemented while activating the flat and non-flat surface programming codes in the checkboxes. The machining operations start to build up by clicking the ‘create operations’ button.

In the same way as with Rough CAM, the user needs to select the blank circular edges, identify the part, blank and check blocks at the beginning of the process. After that, a series of cutting area selections are carried out. The first selection of cutting areas is identified for roughing operations. Referring to the checkboxes on the program GUI, the cutting area selection windows will appear accordingly to assist the surface selections in finishing operations. If both checkboxes are ticked in one finishing orientation, the first selection window requires the user to identify the flat surfaces on the part. Following this, a second window will define the non-flat surfaces to be machined using a ball nose tool. This process can be simplified by inverting the selection made for flat surfaces which will direct the selection to non-flat surfaces. Once completed, these selection processes are repeated again at other finishing orientations. Prior to commencing the machining, all the operations need to be translated into machine codes by using a particular postprocessor. This can be executed through a control button on the program interface. Later, machining codes are produced based on specific file format that depends on the type of CNC machine used. Figure 8.7 illustrates an extended process flow from Rough CAM (Figure 8.6) that emphasizes the cutting area selections.



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File name: Carotid.dll
Files of type: Dynamic Loadable Libraries (*.dll)

CNC Rapid Manufacturing
Please select the number of finishing orientations
by Nafis Osman

CNC-RM Machining Operations
Roughing orientation 89 *degree*
Blank diameter 30 *milimeter*
Finishing orientations 0 *degree* ☑ Flat Surfaces ☑ Non Flat Surfaces
180 *degree* ☑ Flat Surfaces ☑ Non Flat Surfaces
Roughing tool diameter 7 *milimeter*
Finishing tool diameter 4 *milimeter*

Figure 8.8: Process planning flow in CNC-RM

8.5 Program verification

In order to assess the capabilities of both programs in assisting process planning tasks, a series of tests were conducted using different CAD models. With different shapes and sizes, each of the building commands incorporated in the program were examined to validate the applicability in catering for a wide range of products. Seven models were selected to undergo the process planning for CNC-RM by implementing the distinct programs developed. Figure 8.9 shows the models and Table 8.2 summarizes the cutting parameters used in developing the machining plans. The models consist of a mechanical component, propeller, prop mount, shampoo bottle, toothbrush handle, earphone and femur bone. The size of each model is illustrated in Appendix G. Using the general guidelines in visibility analysis, finishing cutting directions for each model were identified. Some models required only two finishing orientations such as the toothbrush handle and mechanical component. Meanwhile, due to the complexity of the shapes, several models need the maximum four cutting angles to completely machine the parts. These include the femur bone, shampoo bottle and propeller. Most of the models have non-flat surfaces during finishing operations but some possessed both flat and non-flat surfaces in one cutting direction. All these differences provide a strong platform to assess the effectiveness of process planning developed inside the programs.

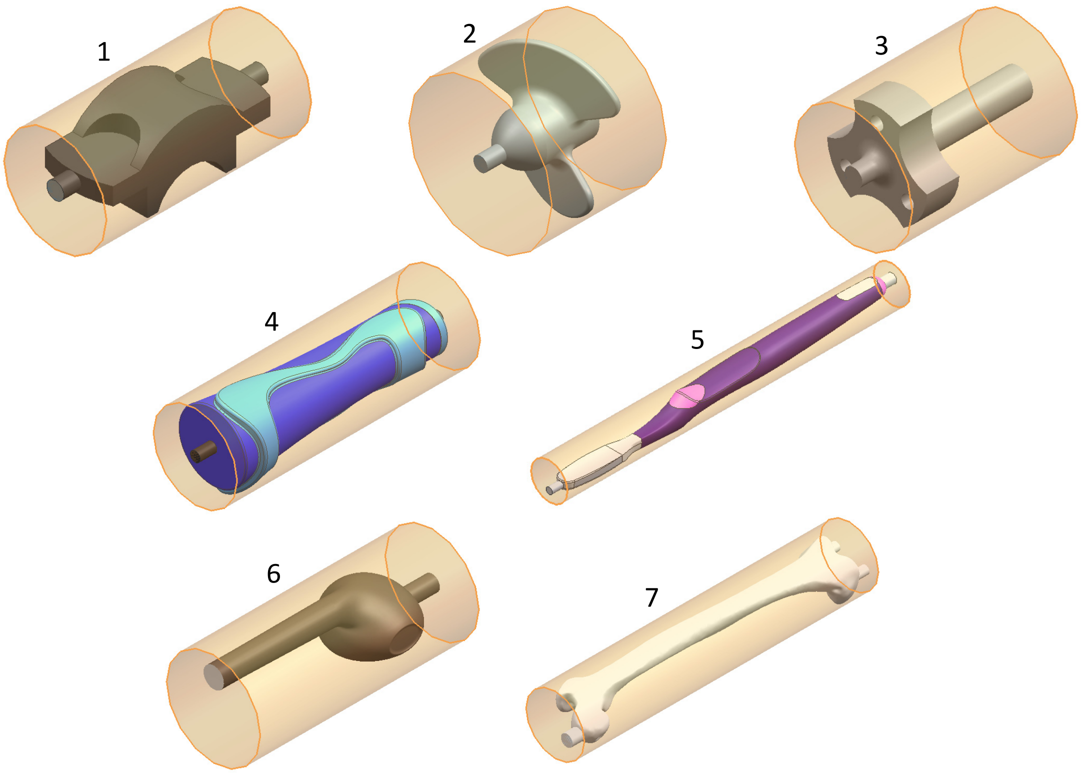

Figure 8.9: Models used in process planning validation (GrabCAD 2014)

Table 8.2: Inputs parameters key in process planning programs

No	Models	Cutting parameters			
		Finishing orientations	Roughing tool size (mm)	Finishing tool size (mm)	Blank diameter (mm)
1	Mechanical component	0^o-180^o	7	4	30
2	Propeller	0^o-90^o-180^o-270^o	10	8	60
3	Prop mount	60^o-180^o-300^o	6	3	20
4	Shampoo bottle	0^o-90^o-180^o-270^o	12	6	50
5	Toothbrush handle	90^o-270^o	9	6	20
6	Earphone	90^o-180^o-270^o	5	3	15
7	Femur bone	0^o-90^o-180^o-270^o	8	5	25

Generally, there are two main criteria used to examine the programs developed in this study. The first one is an evaluation of the adaptability of the programs with different kinds of models and cutting parameters. Hence, the process of building the cutting operations must be possible for each model without any errors or interruptions. This is applicable with the condition that all the procedures for executing the program are handled correctly. The second criterion emphasizes the correctness of the machining operations constructed for each model. It is important to ensure the materials are removed uniformly within the cutting direction to prevent any implications for the tools. There are several ways to carry out the inspection. Cutting toolpaths for different orientations can be observed to detect any missing layers or dissimilarities. If there are any missing layers, the tool needs to remove more material and this potentially causes a failure or breakage. An alternative inspection method is by screening the virtual machining operations executed in the NX interface. Any excess materials are visible and can be detected during the observations. Therefore, simple corrections to the machining program may be required before proceeding with real cutting operations.

8.5.1 Results and Discussion: Optimum roughing orientations set

Several models were used to assess the programs created to develop machining plans for CNC-RM processes. Optimum orientations to execute roughing operations on the part are identified through the Rough CAM program. Table 8.3

suggests optimum orientation values and the estimated time achieved from the series of simulations. Only the first orientation value is required to start the operations, as the three other values are generated accordingly based on the four roughing orientations approach. The data published in this table are extracted from an excel file produced in the simulation analysis. The results indicate the four minimum machining times recorded for each particular part.

Table 8.3: Roughing orientations set generated from Rough-CAM

Models	Result		Roughing orientations
	Orientation	Cutting time (h:min:sec)	
Mechanical component	89°	02:37:07	89°-179°-279°-359°
	87°	02:37:11	
	86°	02:37:16	
	0°	02:37:22	
Propeller	170°	05:58:24	170°-260°-0°-80°
	156°	05:59:31	
	79°	06:06:06	
	168°	06:09:49	
Prop mount	45°	02:26:30	45°-135°-235°-315°
	92°	02:28:09	
	44°	02:28:29	
	94°	02:28:32	
Shampoo bottle	188°	15:29:56	188°-278°-378°-98°
	186°	15:35:50	
	184°	15:36:03	
	177°	15:36:31	
Toothbrush stick	89°	03:16:17	89°-179°-279°-359°
	269°	03:17:26	
	263°	03:17:34	
	88°	03:17:36	
Ear phone	264°	01:27:51	264°-354°-94°-174°
	269°	01:30:09	
	260°	01:30:10	
	294°	01:30:37	
Femur bone	8°	05:35:03	8°-98°-198°-278°
	359°	05:36:45	
	90°	05:36:52	
	278°	05:37:38	

The program succeeds in the analysis of all of the tested models. It controls the machining simulation to work continuously based on an orientations range determined by the program. Generally, cutting times vary based on the size and shape of the parts. Therefore, large parts such as the shampoo bottle took longer to machine compared to smaller parts such as the earphone. As mentioned earlier, the simulations are carried out by integrating together the finishing operations and utilizing a single flat end mill tool. This replicates the completeness of the cutting operations to produce one part and generate reliable estimated cutting times. Interestingly, using a single setup in the program GUI, the analyses are carried out continuously without user interruption. The simulation usually takes a considerable time dependent on the range of the analysis. Hence, the user can just leave the program to run without any supervision until the result is generated.

Further verification is performed by observing the rough cutting toolpath on the part. The observation would be based on the cutting layers and also the continuity of the operations from one orientation to another. As the operations incorporate in-process workpiece, the cutting operation must only be executed on the remaining material left from previous operations. This is important to avoid air cutting and prevent unnecessary toolpaths. Figure 8.10 shows the cutting tool movement to cut the propeller model. Uniform cutting layers can be seen clearly which indicates the right cutting operation has been built by the program. In addition, the toolpaths generated only cover the remaining material left from the previous operation. These outputs signify the ability of the program to run and control the simulations in order to identify optimum roughing orientations.

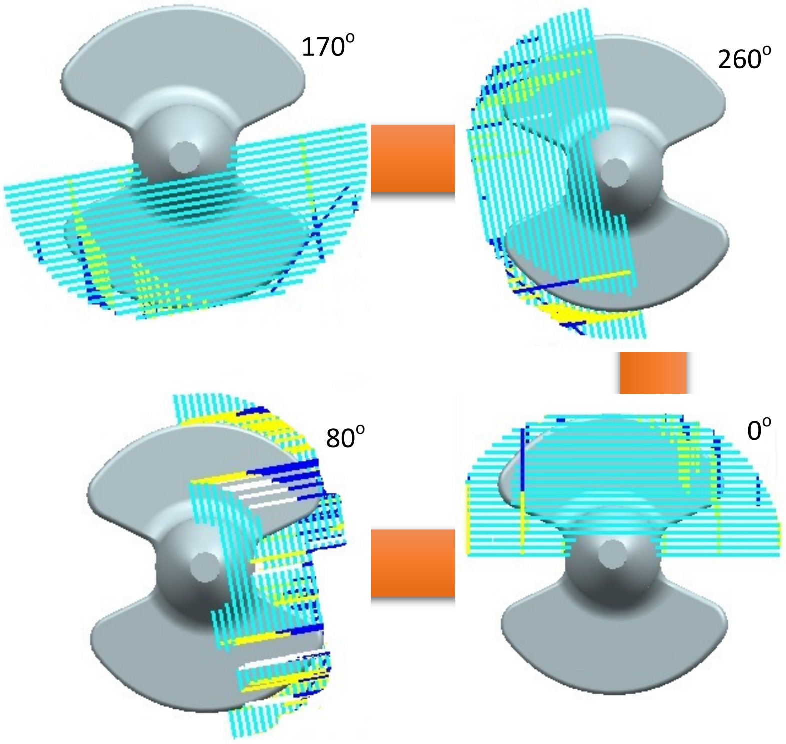

Figure 8.10: Rough cutting toolpaths for propeller model

8.5.2 Results and Discussion: CNC-RM machining operations

A series of machining operations were created using the results gained from the Table 8.3. The roughing orientation values are used as an input for the second program to construct the real machining operations. Overall, the program manages to build the cutting operations correctly including both roughing and finishing operations. Moreover, different cutting tools are integrated during the finishing operations to cater for flat and non-flat surfaces. Table 8.4 compiles the number of operations and estimated cutting time for each model. The results can be viewed from several perspectives. First, for the orientations that contain both flat and non-flat surfaces, two finishing operations are performed in one cutting direction. Hence, the number of operations is increased compared to the number of orientations used. The mechanical component model describes this situation. The rest of the models possessed a similar number of orientations and operations. These models utilize only one cutting tool which is a ball nose end mill to finish cut the part. Therefore, only one operation was executed for each orientation.

Roughing operations are performed through four cutting orientations and are standardized for all models.

Table 8.4: Result obtained from the program used to construct CNC-RM machining operations

Models	Number of orientations	Number of operations	Estimated cutting time (hour:min:sec)	Planning time (min:sec)
Mechanical component	6	8	03:10:31	03:24
Propeller	8	8	08:40:00	07:30
Prop mount	7	7	02:11:55	04:15
Shampoo bottle	8	8	08:56:40	05:22
Toothbrush stick	6	6	04:22:33	02:07
Ear phone	7	7	01:30:30	02:37
Femur bone	8	8	04:05:21	04:00

Data from Table 8.4 can be compared with the data in Table 8.3 which shows the difference of estimated cutting time between the two programs. Cutting times suggested in this section incorporate different types of tools in finishing operations, whereas section 8.5.1 only depended on a flat end mill. There are some models that indicate higher cutting times when using different cutters on part surfaces. These include the mechanical component, propeller and toothbrush handle. These results are expected as machining time is highly dependent on part geometries. Some models exhibit minimum cutting time by using different tools during finishing operations. After all, the main goal of the integration is to produce quality parts by minimizing the stepping appearance. The planning time section indicates the time spent in the process planning to build the machining operations for particular models. The times are recorded starting from keying in the machining parameters to the program GUI, followed by selection tasks and finish once the whole operations sequence has been constructed. The times range between 2 and 8 minutes and generally depend on part complexity. Indirectly, this result shows the effectiveness of the customised program (CNC-RM CAM) designed to conduct the process planning tasks in CNC-RM. Standardizing and constraining the machining parameters has improved the planning process for CNC machines. Moreover, it has substantially reduced the processing time and expertise required to build the machining program.

On the other hand, the program manages to construct finishing operations based on part surfaces. Several selection windows allow the user to guide the tools on appropriate part surfaces. Consequently, the machining operations can be developed effectively especially when two different tools are used in one cutting orientation. Figure 8.11(a) visualizes the finishing operations on the mechanical component that integrates two cutting tools. The first operation machines the flat surfaces followed by the second operation that covers the rest of cutting areas. The materials are completely removed until a certain cutting level that has been setup in the program. If one cutting tool were used, then the single operation is carried out to machine all surfaces on the part as illustrated on Figure 8.11(b). In this example, only non-flat surfaces are present and thus a ball nose end mill is selected to finish cut the part. Once all criteria have been verified, the machining codes can be produced by activating the ‘generate machine codes’ button in the program. By default, the machining file is directed to be saved on the desktop folder.

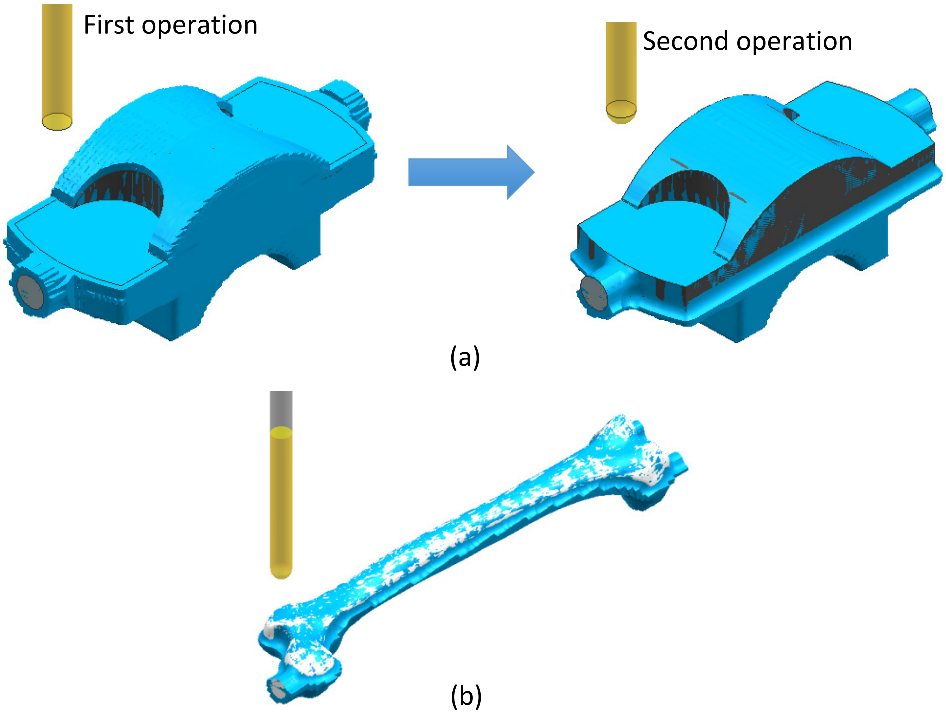

Figure 8.11 (a) Finishing operations on flat and non-flat surfaces and (b) Finishing operation on non-flat surface.

8.6 Process review

Basically, the rapid generation of machining plans is realized through a program described in section 8.4. Initially, the sacrificial supports are attached to the CAD model by constructing small cylindrical shapes at suitable locations on the part. Prior to running the program, pre-process analyses are performed to identify several machining parameters required in CNC-RM processes. The first analysis relates to part visibility and defines the finishing orientation values (Frank 2003). Meanwhile, optimum orientations for the roughing process are determined through another analysis as described in section 8.3. Once the outputs are established, a series of machining operations are constructed automatically within the CAD interface. Then, machining codes can be generated through push button instructions available in the program GUI. The file is saved in a specific location as defined internally by the program codes. The planning process is completed with the machine setups that mainly involve the preparation of the workpiece and establishing machine coordinate system. In the execution stage, the workpiece will be continuously machined at several orientations and then, removing the support structure formed on the machined part completes the process.

In comparison, a general process planning flow in AM starts with the conversion of a CAD model into the STL file format. Commonly, there is a possibility of error while converting the file. Thus, correction steps are essential using various repair software tools. Next, several process parameters need to be defined which include build orientation, support structure, layer thickness and path planning. Various approaches have been developed as assisting tools to optimise the operation and guide the process definition (Kulkarni et al. 2000). These can be considered as pre-process analyses that will generate efficient building operations. Then, a setup is performed on the AM machine. Depending on the type of machine, this can be selected based on default settings or from previous setups that have been recorded on the machine (Gibson et al. 2010). This simplifies the machine setup load and speeds-up the operation. Finally, the part is built and the process is completed with necessary cleaning and finishing processes.

In general, the planning approach employed in AM and CNC-RM processes exhibit a certain level of automation throughout the process flow. The task of providing process parameters can be considered as semi-automated where the user needs to get the result from the pre-process analyses conducted earlier. Although AM technologies are capable of generating the parameters from the supplied machine software, this is not always applicable especially when dealing with optimization. Hence, numerous algorithms are introduced to improve the process efficiency. Similarly, process planning in CNC-RM utilizes several algorithms to provide optimum process parameters as inputs to the main program. Most of the analyses are computational and therefore are performed automatically to generate the required outputs. The implementation of these algorithms has minimized the complexity of CNC machine process planning such that it becomes equivalent to AM process planning. Therefore, the rapid process requirement has been fulfilled through the planning tools developed in this study. However, simple manual tasks are still present in machine setup particularly to clamp the workpiece to the indexers. Figure 8.12 summarizes and compares the process flow between AM and CNC-RM operation.

It is important to note that the planning tools developed in this study are only intended to cater for roughing orientations and tools integration issues. Basically, there are two important developments addressed by the CNC-RM CAM program discussed in section 8.4. The first is that it acts as a main framework of CNC-RM processes and compiles all the parameters required and builds the machining operations. Prior to the build-up processes, other analyses and tools can be used to identify optimum values of each parameter. These include the Rough CAM program developed in section 8.3. Additionally, there are other optimization tools that have been developed from past studies. For example, an algorithm developed to determine optimum tool sizes can be used to ensure proper combination of cutting tools (Renner 2008). Similarly, the sacrificial support structure on the part can be designed efficiently using an automated fixture design approach (Boonsuk et al. 2009). Another approach can be implemented to determine appropriate tool geometry, diameters and machining parameters considering part accessibility (Luo et al. 2013). All these developments inherit an automatic ability which definitely will minimize the planning load and at the same time preserve the process efficiency. The second purpose of CNC-RM CAM is to integrate the cutting tools in finishing processes. The cutting area selection tasks are performed manually where user needs to interpret the surfaces and guide the selection. However, considering various computational and intelligent systems developed, this task could be simply automated by plug-ins to the CNC-RM CAM program.

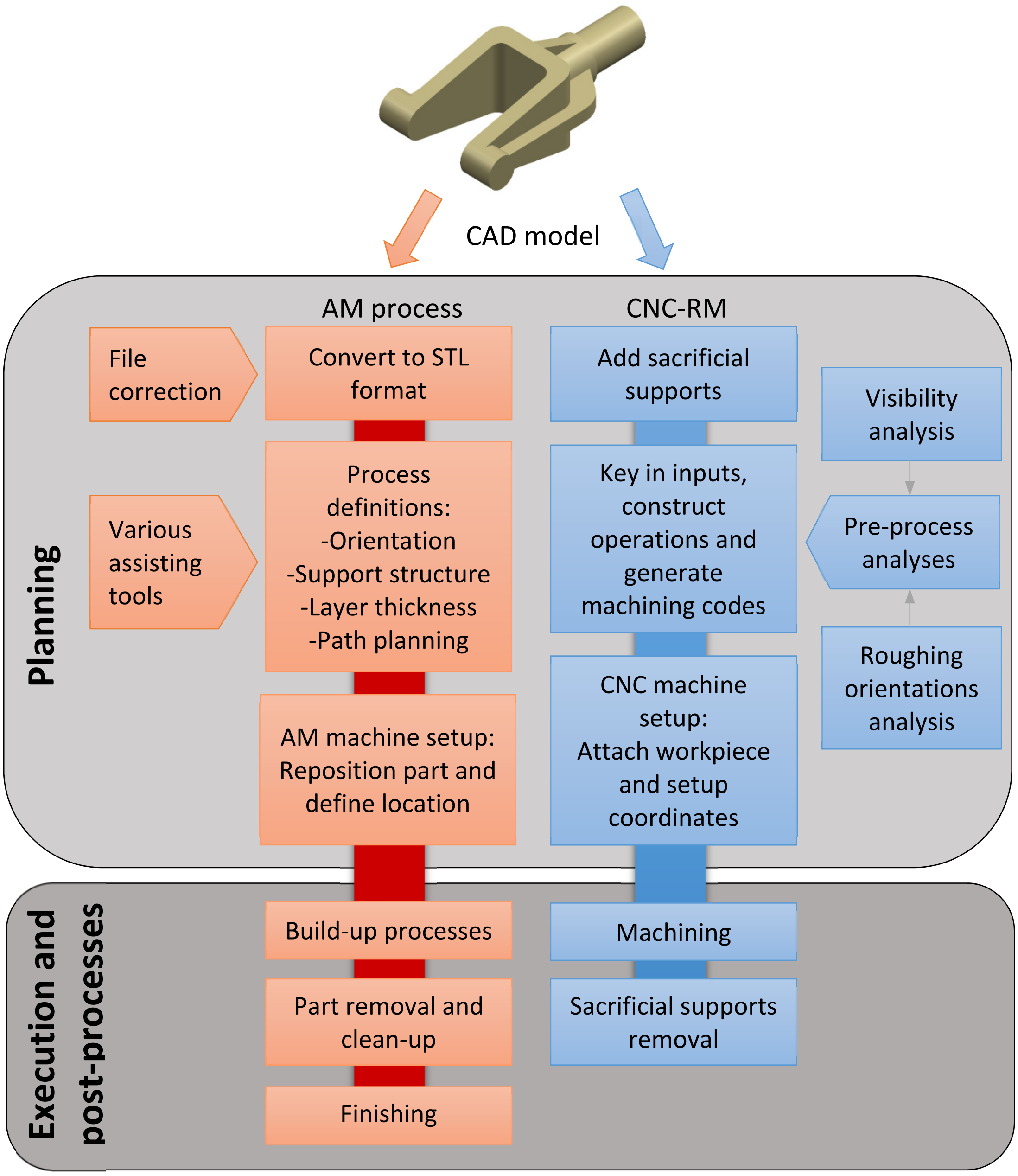

Figure 8.12: Process flow between AM and CNC-RM operation.

8.7 Summary

This chapter has described process planning development to execute the two distinct approaches suggested in this research. Basically, customised programs are developed to work within the CAD interface and construct machining operations effectively. The main purpose of the programs is to assist the development of machining operations based on CNC-RM processes. The programs developed have shown that a large number of machining operations can be controlled and performed with a minimum number of inputs. Customised coding within the programs has worked effectively and is well-connected to prominent CAD software. Hence, the generation of machining operations is carried out within the same interface and directly communicates with the user. Both programs developed have been successfully verified by processing a number of CAD models. Moreover, the overall planning flow is compared to the AM processes in order to justify that the rapid requirement has been achieved. Thus, it allows the new approaches to be fully incorporated into the established process planning for CNC-RM. However, the current development was not specifically designed to optimise the number of tasks involved in the planning phase. Therefore, it incorporates all required tasks to build machining operations and there is the possibility of tasks that are not properly connected between each other. For example, the determination of roughing tool size can rely on the diameter of workpiece. But, considering the program flexibility, these two parameters are designed independently. Considerably more work will needed to manage planning tasks effectively especially on parts that require many selection inputs from the user.

CHAPTER 9

DISCUSSIONS AND CONCLUSIONS

9.1 Introduction

This thesis has investigated the potential of subtractive processes particularly for CNC machining in the field of RM. The research was designed to enhance the capabilities of CNC machining to rapidly fabricate end-user products through the advancement of tooling and machining methods. Returning to the problems described at the beginning of the thesis, it is now possible to state that feasible solutions have been formulated to assist the CNC-RM processes.

9.2 Research work

The work begins by assessing the possibility of improving the implementation of CNC machines for rapid processes. The review of current literature discussed in section 2.4 has initiated the idea of improving the roughing operations and integrating different end mill geometries into the process. Thus, preliminary studies were conducted to examine the feasibility of the proposed ideas. The results discussed in section 3.3 have broadened the possibilities for improving the current implementations of CNC machining for RM. Following this, the main investigation started by manipulating the cutting orientations and observing the effects on machining times. Several methods were explored that were based on adding more roughing operations (Add-O: 1 and 2 orientations) and manipulating the orientations (Ind-O: combination of 3 and 4 orientations) that were already part of the process. The details of the proposed methods have been discussed in section 4.2. Using four different models, simulation analyses were performed to evaluate all the eight methods including the Frank (2003) original approach. During the simulation, several parameters were extracted which mainly consisted of estimated cutting times. The results are then compared based on predefined assessment criteria and an optimum solution is proposed.

Further development proceeded by examining the implications of cutting tools integration within the machining processes. Selection of tool geometry and surface classification were defined before carrying out the simulations. Hence, flat and ball nose end mill were selected to machine flat and non-flat surfaces respectively. Using similar models in chapter 4, machining simulations were run in NX software which subsequently produced the cutting time data. The analyses were extended further using VERICUT® software to identify remaining excess volumes on the machined part. These results were then inspected to justify the proposed approach. The work described in chapters 4 and 5 showed another possibility of improving CNC-RM processes, particularly in simplifying the finishing orientations for non-complex parts. Thus, the simulation analyses were extended in chapter 6 to identify the effect of using only two finishing orientations. By adopting the proposed approaches developed in this study, machining simulations were performed on non-complex models to verify the implications of minimizing the finishing orientations.

From the beginning of the research, several customised programs were developed to handle the process planning phase. However, these programs are still in the development stage and are not completely automated. These programs were expanded and strengthened through a series of analyses. The programs were built using advance tools in the CAM system that translate the instructions into the programming language. The codes are then modified and customised to provide full control on the operation build up. In order to validate the simulation work, machining experiments were performed incorporating all the proposed approaches. The two major objectives of the experiments were to evaluate the process efficiency and the programs developed to execute planning tasks. The real cutting times were recorded for comparison with the machining times proposed from simulations. Moreover, surface analyses were performed on several locations on the machined parts based on flat and non-flat surfaces. Then, any unexpected machining conditions were identified and handled through modifications of the process planning. Finally, the research was completed with extensive development and verification of the planning programs. Two distinct programs were introduced to handle the roughing process improvement and integrating the cutting tools. This was discussed in detail in chapter 8. Further validations were carried out virtually using seven different models. Overall this represents a primary development that will realize a rapid machining system for CNC-RM processes

9.3 Achievements

Several achievements were gained from the study conducted into developing the CNC-RM process. These can be summarised as follows:

- ❖ The proposed method to execute roughing operations through four independent orientations has made several contributions.
    - It was shown that the four independent orientations proposed for rough cuts manage to increase the volume of material removed. Thus, finishing operations are simplified with less material left for finishing processes. This has resulted in a significant time reduction in finishing operations and minimized the total machining time.
    - The cutting tool length is minimized which improves efficiency and tool life. Instead of cutting at the furthest possible depth, the new approach only requires the cutting tool to machine to the centre of the cylindrical workpiece. Indirectly, the selection of tools becomes more flexible and is not restricted only to long cutting tools.
    - Any possibility of thin material formation is avoided which maintains good machining practice in 4th axis machining operations. Roughing using a predefined four orientations set effectively removes the bulk of the material leaving a considerable amount for finishing operations.

Hence, thin webs are no longer an issue in determining the finishing orientations. Consequently, the orientations can be widely selected and it is possible to adopt a minimum of two orientations.

- ❖ The use of different cutting tool geometry in finishing operations has improved the efficiency of CNC-RM operations.
    - Depending on part geometries, the cutting time spent to machine the parts reduced when multiple tools were used in the finishing operations. This is described in section 5.3.1 that highlights the simulation results.
    - Flat end mills are capable of handling flat surfaces whereas ball nose end mills catered for non-flat surfaces. Simulation analyses indicate minimum excess volume left on the part compared to operations that rely only on flat end mills.
    - The simulation results were confirmed by analysing the parts produced in the experiments discussed in Chapter 7. Visual inspection indicates an obvious staircase effect if the process used only flat end mill tools. Integrating cutting tools improved the surface quality. The roughness values fall within an acceptable range for CNC machining processes and are far better than those obtained from other RM processes.
- ❖ Two customised programs were developed to assist the planning stage of CNC-RM processes.
    - The first program (Rough CAM) is used to identify the best orientations set for roughing processes. It analyses all possible orientations sets to execute roughing operations and produces cutting time data at the end of the simulation. This data can be easily interpreted to identify which orientations give minimum machining time.
    - The second program (CNC-RM CAM) was particularly developed to build the whole operation whilst integrating multiple tools in finishing processes. It provides input sections to key-in optimum parameters that can be defined from other optimization tools. Moreover, the surface selection is carefully guided through pop-up windows when the program

is activated. The machining file is directly generated through a push button provided on the program user interface.

- Both programs facilitate the operations build-up process with minimum human intervention and embed substantial levels of automation in the planning stage. The numerous tasks of building the operations were simplified at the same time as providing a truly rapid machining system.

9.4 Objectives review

The achievements of work carried out in this research have fulfilled the aim and objectives stated earlier. The research objectives can be reviewed in detail as follows:

Objective 1: Investigate a different strategy to improve roughing operations by manipulating the cutting orientations.

In the simulation studies, several approaches have been discussed in chapter 4 to determine feasible methods to improve the roughing operations. With different combinations of orientations sets, the total machining times were considered as the constituent of roughing, finishing and non-cutting times. Based on the evaluation criteria defined in this study, roughing through four orientations (0^o-90^o-190^o-270^o) is denoted as a solution to improve the operation. This strategy effectively executed roughing operations and resulted in lower machining times, higher rough cutting times and protected against any inefficient cutting conditions. It is proven in the simulation models and the machining experiments to produce real parts.

Objective 2: Investigate the influence of different cutting tools and formulate the integration approach to be implemented in CNC-RM processes

Cutting tool geometry had a major influence on the surface quality of the machined parts. Based on the series of analyses conducted, using multiple tools in finishing operations managed to improve surface appearance and minimized excess material. Classification of flat and non-flat surfaces in one orientation provides clear cutting regions for each tool. Referring to current literature discussed in section 5.2.2, a flat end mill is recognized as appropriate for machining flat surfaces. Meanwhile, a ball nose end mill is well-known for dealing with sculptured surfaces and is appropriate for dealing with non-flat surfaces in CNC-RM processes. With this surface classification in addition to the CNC-RM CAM program, cutting tool integration is formulated effectively and is highly suitable for implementation in RM processes.

In general, both objectives suggest the improvement in the production stage during machining process. However, since the implementation is specifically for RM, the planning operations need to be scrutinised. Therefore, in addition to improving the machining and tooling approach, the establishment of a rapid machining system is also a substantial outcome of the study. It was necessary to develop software implementations in parallel to the approaches suggested. This was realised through the implementation of a programming language generated within the CAD/CAM system. As a result, two programs known as Rough CAM and CNC-RM CAM were introduced and described in sections 8.2 and 8.3. Both programs are completely developed with proper user interfaces that can run and control the operations build-up in the CAD/CAM system.

9.5 Contributions to knowledge

The findings from this study make several noteworthy contributions to the current implementation of CNC machining for RM processes. These are:

- A new method to improve roughing operations has been formulated. Without complicating the planning tasks, the optimization is carried out by manipulating the cutting orientations rather than the common approach of controlling the cutting parameters.
- The improvements made in rough cutting times lead to a reduction in total machining time. This complies with the requirement for RM to produce parts with the least production time.
- Introduction of four roughing orientations inculcates good machining practice. Several benefits gained from this approach include the avoidance of cutting at

the furthest depth, cultivation of good cutting conditions, prevention of tool failure and minimization of part defects.

- Providing different types of end mills in finishing processes has enhanced the quality level achievable for the machined parts. Hence, different kinds of surfaces can be machined efficiently which bring the parts close to the expected dimensions.
- A surface classification method has been proposed that is beneficial to the integration of different end mill tools within a single cutting orientation. This method effectively partitions the cutting regions, shapes the different surfaces and at the same time avoids any redundant machining areas.
- Unlike conventional planning practices, CNC-RM process planning is supported by the latest CAM technology that allows other independent programs to take control and rapidly develop the machining codes. Hence, two customised programs, Rough CAM and CNC-RM CAM have been designed and implemented. These programs run within the CAM interface which is primarily used to define the cutting parameters and control the operations build-up process.
- The programs have been built from a common programming language known as Visual Basic. Therefore, any modifications and improvements can be performed to execute specific functions. On top of that, any optimization algorithms can be directly incorporated into the codes and consequently enhance the functionality.
- Incorporating programming in CAM systems can be a feasible solution to enhancing communication between the user and the system which indirectly increases the flexibility of CNC machining in handling a wide range applications. In this research, the planning methods employed manage to minimize human dependency and manual tasks that previously constrained the wider application of CNC machining
- Instead of generating the machining operations, the planning tools designed in this research are also used to control the simulation analysis automatically within the CAD/CAM interface and propose optimum cutting parameters. The analyses are capable of running continuously without human intervention.

9.6 Limitations and future recommendations

Several limitations in this study need to be acknowledged. First, the machining simulations conducted to search for optimum roughing orientations are considered as a time consuming analysis. Depending on the range of orientations and part complexity, the analysis can take up to several hours. The main reason for this is due to the simulation approach that rebuilds all the operations once a new orientation value is introduced. However, in long production runs, the time taken for simulation becomes insignificant in comparison with the total time taken to produce the parts. As an alternative, the roughing operations can still be developed through random orientation values proposed by the user. In this case, the machining time generated is not a minimum but good machining conditions including the cutting levels are preserved.

Secondly, the NX software is incapable of translating some of the cutting options into the programming codes. For example, the trim boundary option in defining the cutting areas selection. Since the code cannot be produced, it makes the option unavailable and causes the surface classification task to be solely dependent on user selection. Consequently, this tends to cause redundant cutting areas since the boundaries cannot be defined by the programs. However, this is not always the case as it possibly occurs when dealing with complex parts that contain small selection areas.

Another limitation is related to the compatibility of the CAM system in developing the machining operations and adaption to various geometries between the cutting orientations. In some isolated cases, the system is incapable of developing uniform cutting toolpaths and causes some of the cutting levels to be missed. The condition is shown in Figure 9.1. Consequently, this will force cutting tools to suddenly remove large volumes of material and potentially cause breakage. The adaptability issue and software errors are expected to be the source of this problem. Nonetheless, the introduction of the latest version of NX software or some modification of the depth of cut value is expected to resolve the problem.

Therefore, it is worthwhile to observe the cutting toolpaths generated by the system before running the machining to prevent any mistake.

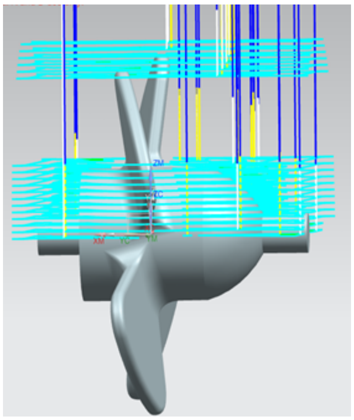

Figure 9.1: Missing cutting layers generated from CAM system

Basically, this research has proposed several approaches with specific methodologies that are ready to be implemented in the CNC-RM processes. However, there are still many areas of improvement that can be undertaken in future research. Hence, several possible areas for further investigation are listed as follows:

- The proposed roughing methodology permits the possibility of executing finishing operations within two opposite cutting orientations. Particularly for non-complex parts, the machining orientations can be easily proposed by the user. Hence, visibility analysis can be skipped thus minimizing the processing steps. However, a proper guideline needs to be established to determine when the two cutting orientations are sufficient to produce the part. Moreover, advanced programs can be developed to find an optimum two orientations set. This will be totally related to the level of complexity of the machined parts. Having this guideline will provide a clear cut decision whether or not to skip the visibility analysis.

- While integrating the cutting tools, the current system requires an input from the user to select particular types of surface that are based on cutting directions. These selections are used to partition the toolpaths based on specific cutting regions. Consequently, this task seems to limit the automatic capability of the system. Therefore, it is worthwhile to expand the system abilities to recognize different kinds or surfaces in any orientation. Any available computational algorithms can be embedded in the program particularly to perform the surface selection task. Alternatively, it could also be automatically guided through surface colours with priorities determined before developing toolpaths.

- Previously, the determination of finishing orientations was totally dependent on part visibility. With the introduction of a surface classification for tool integration, it is possible to include this as a consideration in defining the orientations. For example, the first orientation can be determined not only based on a wide coverage area, but also to cover large flat surfaces. This allows full utilization of a flat end mill to machine the area and produce fine quality surfaces.

- The programs developed to assist CNC process planning required several cutting parameters as inputs. Since there are massive tasks incorporated in the programs, some of the inputs can be possibly connected to other parameters which later minimize the information required from user. For example, the decision on cutting tool selection can be dependent on the size of workpiece. Having less to key in will simplify and speed up the pre-processing for CNC-RM.

- Another development could be to focus on material compatibility in the designed systems. Currently, the system is only capable of constructing machining operations for parts made of aluminium. Selection of materials will influence several cutting parameters embedded inside the programming codes. In order to machine other materials, the program needs to employ different cutting parameters that are based on the selection. Therefore, a materials and cutting parameters database is necessary to make the system adaptable to the selection and to produce effective machining operations.

The findings of this study have a number of other implications particularly in CNC machining processes. First, the method of surface classification for tool integration could also be used in general machining applications. Rather than developing toolpaths based on geometric features on the part, assigning cutting tools based on part surfaces would be less complicated. Meanwhile, the implementation of customised programs developed for process planning can be extended to ordinary machining operations. Basically, the program contains the codes to develop several milling operations based on cutting orientations. Thus, taking a portion of code that represents one milling operation allows the program to rapidly create operations for conventional CNC machining processes.

As a conclusion, the developments proposed in this study manage to speed-up the planning process for CNC machining, minimizing the machining time while at the same time enhancing part quality. From an economic perspective this broadens the opportunities for cost saving in CNC machining. Certainly, minimizing machining time will lead to a reduction in power consumption, tool usage and ultimately the overall cost of production. Taken together, the results of this research support the idea of strengthening the establishment of CNC machining in RM processes.

9.7 Publications

Publications emerging from this thesis are stated as follows:

1. OSMAN ZAHID, M.N., CASE, K. and WATTS, D., 2013. Optimization of Roughing Operations in CNC Machining for Rapid Manufacturing Processes, In E. Shehab, P. Ball, & B. Tjahjono (Eds.), *Advances in Manufacturing Technology XXVII, the Proceedings of the Eleventh International Conference on Manufacturing Research, ICMR 2013* (pp. 233-238). Cranfield University, UK, 19-20 September 2013.
2. OSMAN ZAHID, M.N., CASE, K. and WATTS, D., 2014. Cutting Tools in Finishing Operations for CNC Rapid Manufacturing Processes: Simulation Studies. F. Rehman, N. Woodfine, & R. Marasini (Eds.), *Advances in Manufacturing Technology XXVIII, the Proceedings of the Twelfth International Conference on Manufacturing Research, ICMR 2014* (pp. 163-168). Southampton Solent University, 9-11 September 2014.
3. OSMAN ZAHID, M.N., CASE, K. and WATTS, D., 2014. Cutting Tools in Finishing Operations for CNC Rapid Manufacturing Processes: Experimental Studies, *Proceedings of the International Conference on Manufacturing Engineering and Technology*, 19 June 2014, Istanbul, pp. 1188-1192.
4. OSMAN ZAHID, M.N., CASE, K and WATTS, D. 2014. Cutting Tools in Finishing Operations for CNC Rapid Manufacturing Processes: Experimental Studies, *International Journal of Mechanical, Aerospace, Industrial and Mechatronics Engineering*, **8**(6), pp. 1071-1075.
5. OSMAN ZAHID, M.N., CASE, K. and WATTS, D., 2014. Optimization of Roughing Operations in CNC Machining for Rapid Manufacturing Processes. *Production & Manufacturing Research,* **2**(1), pp. 519-529

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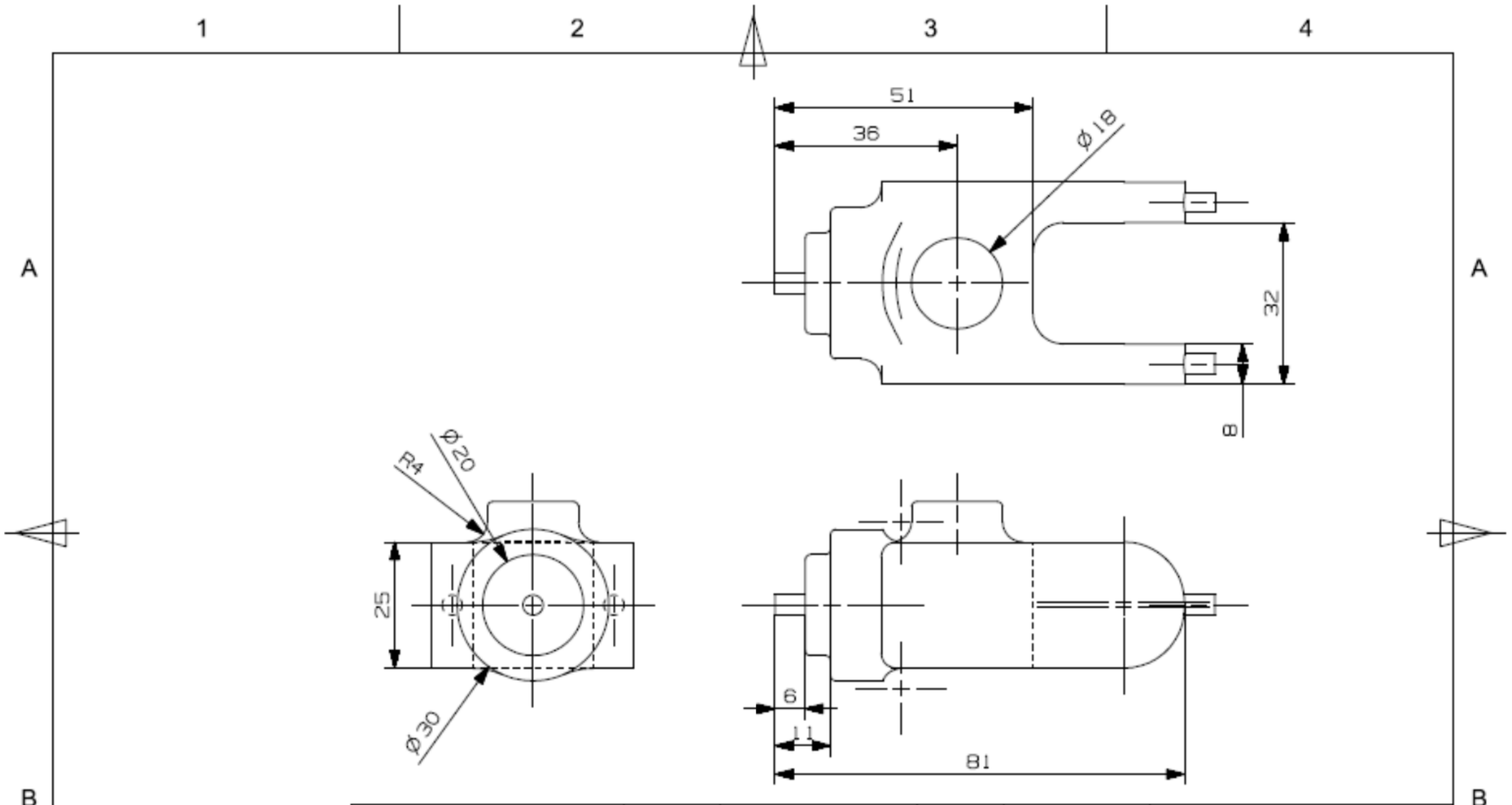
Appendix A:

Dimensional sketches for drive shaft, knob, salt bottle and toy jack models



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ANGULAR TOL UOS	±0,5°	ALL DIMENSIONS MM		DRAWN BY	M. NAFIS	
Loughborough University				STUDENT ID	B133255	
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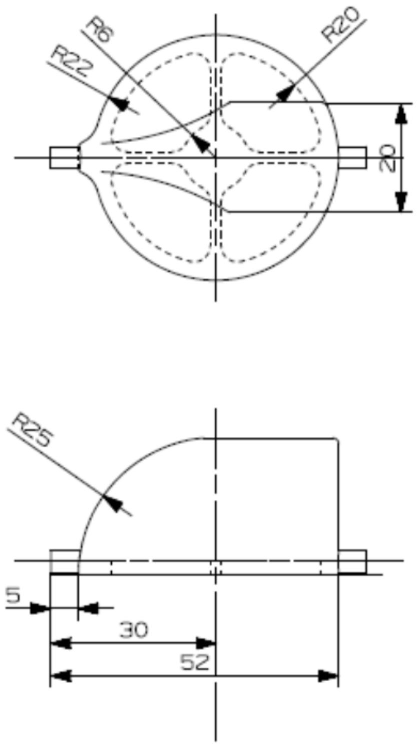
				DRAWING NO.	-	
				DATE	REVISION	SHEET
				21/11/2014	-	1 OF 1



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ANGULAR TOL UOS	±0,5°	ALL DIMENSIONS MM		DRAWN BY	M, NAFIS	
Loughborough University				STUDENT ID	B133255	
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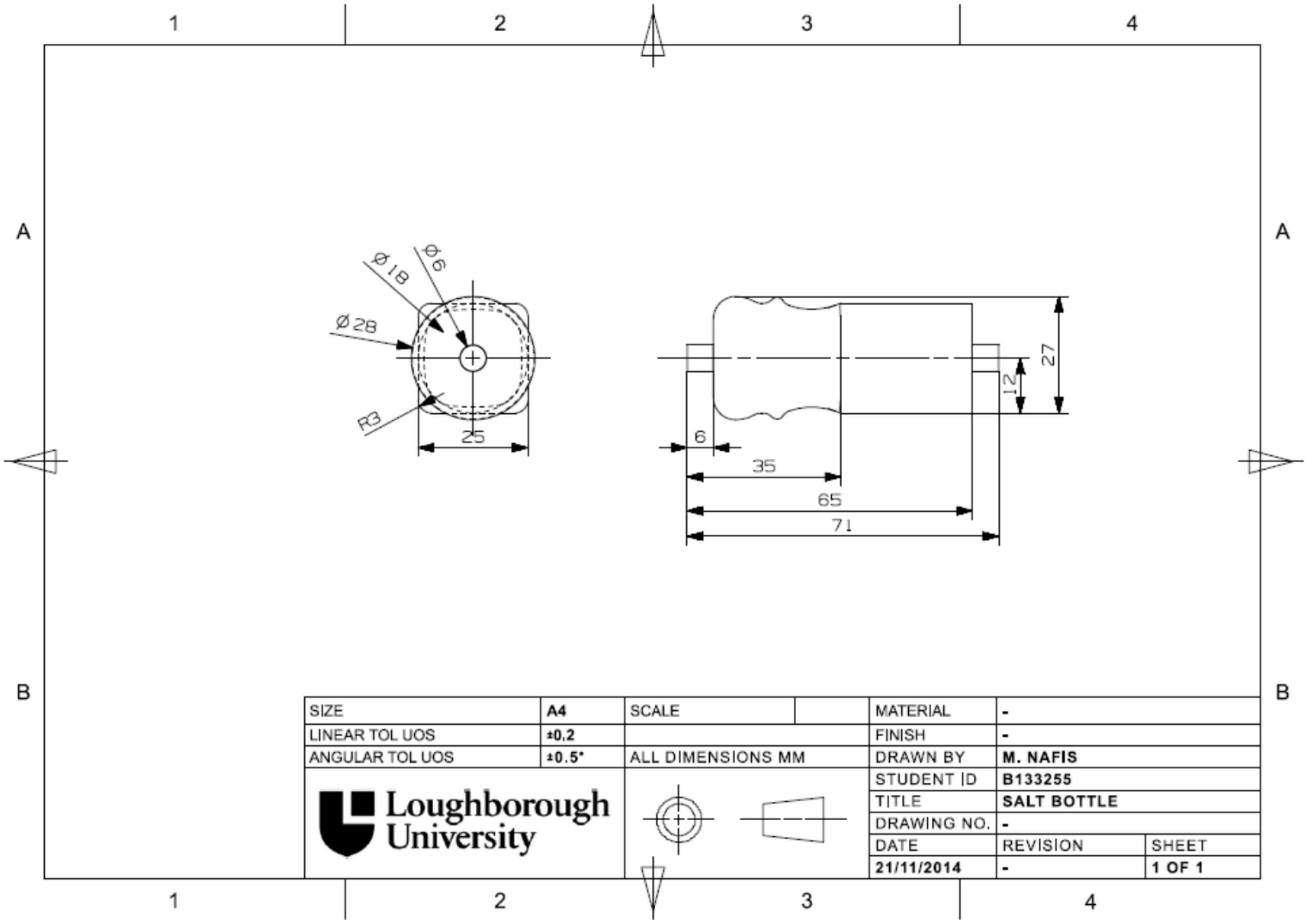
				DATE	REVISION	SHEET
				21/11/2014	-	1 OF 1



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Loughborough University				STUDENT ID	B133255	
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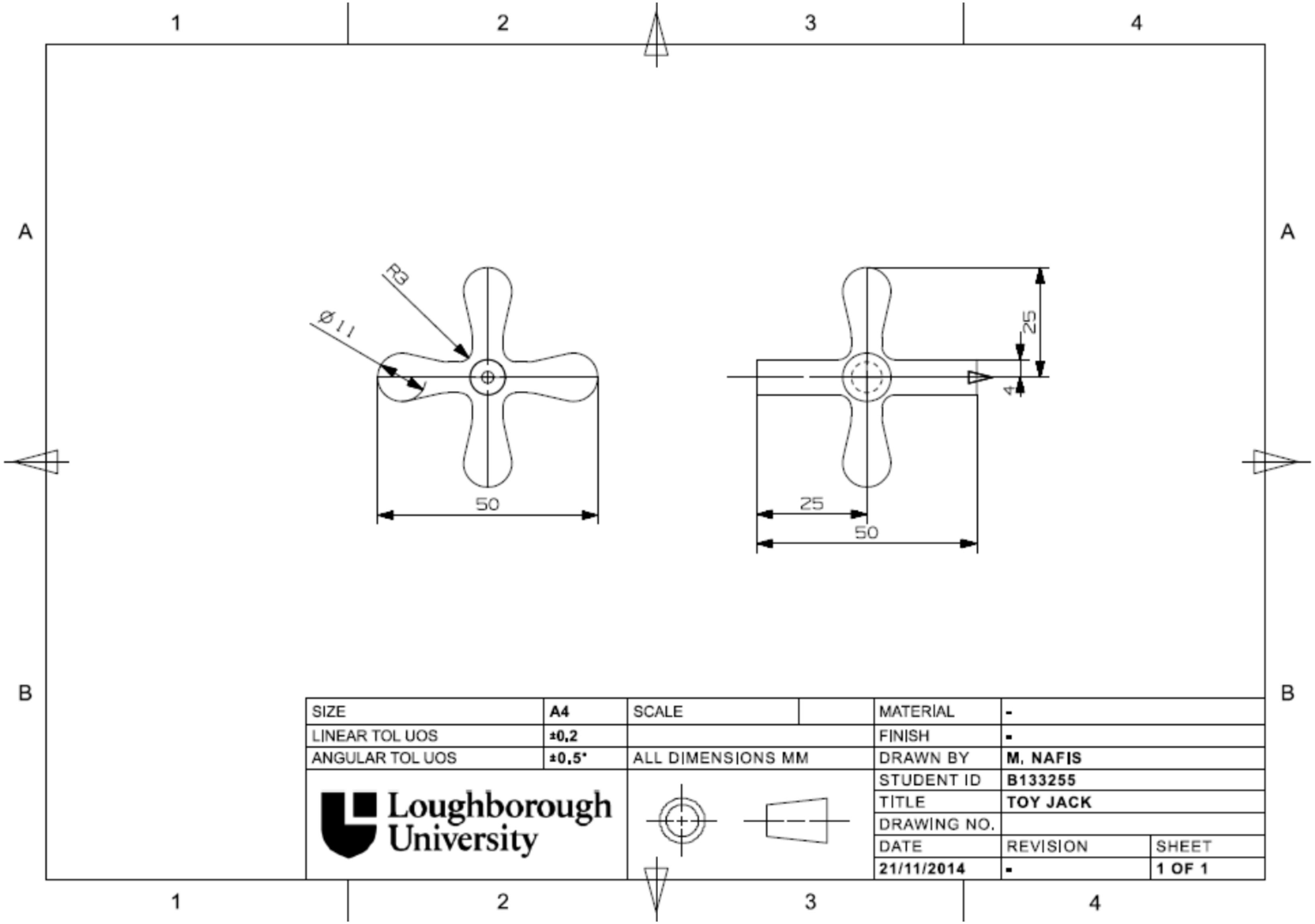
				DRAWING NO.	-	
				DATE	REVISION	SHEET
				21/11/2014	-	1 OF 1



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Loughborough University				STUDENT ID	B133255	
				TITLE	TOY JACK	
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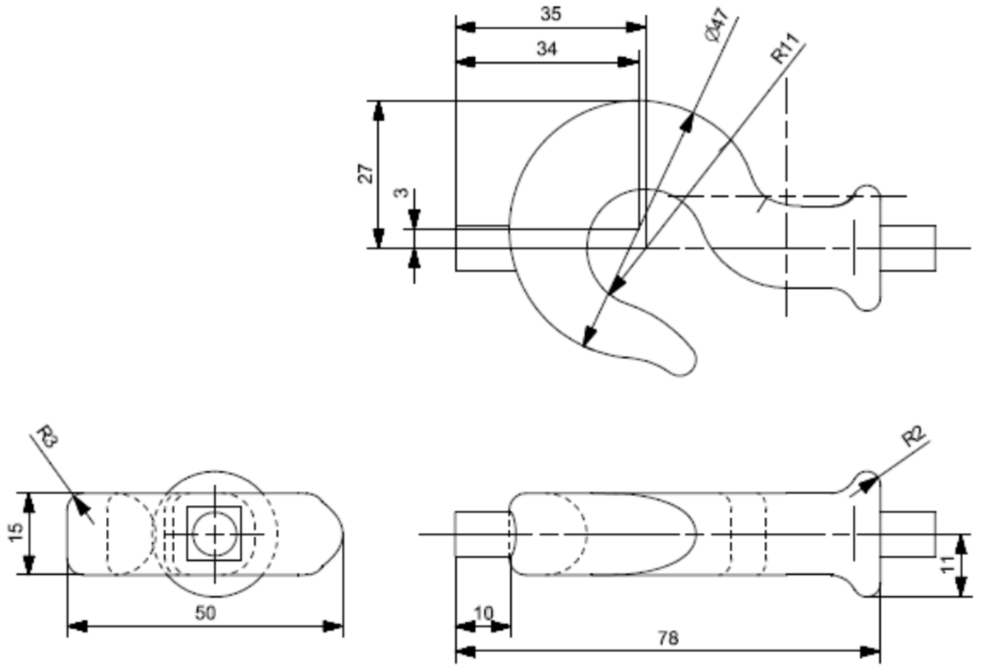
				DATE	REVISION	SHEET
				21/11/2014	-	1 OF 1

Appendix B:

Dimensional sketches for crane hook and vehicle gear knob models



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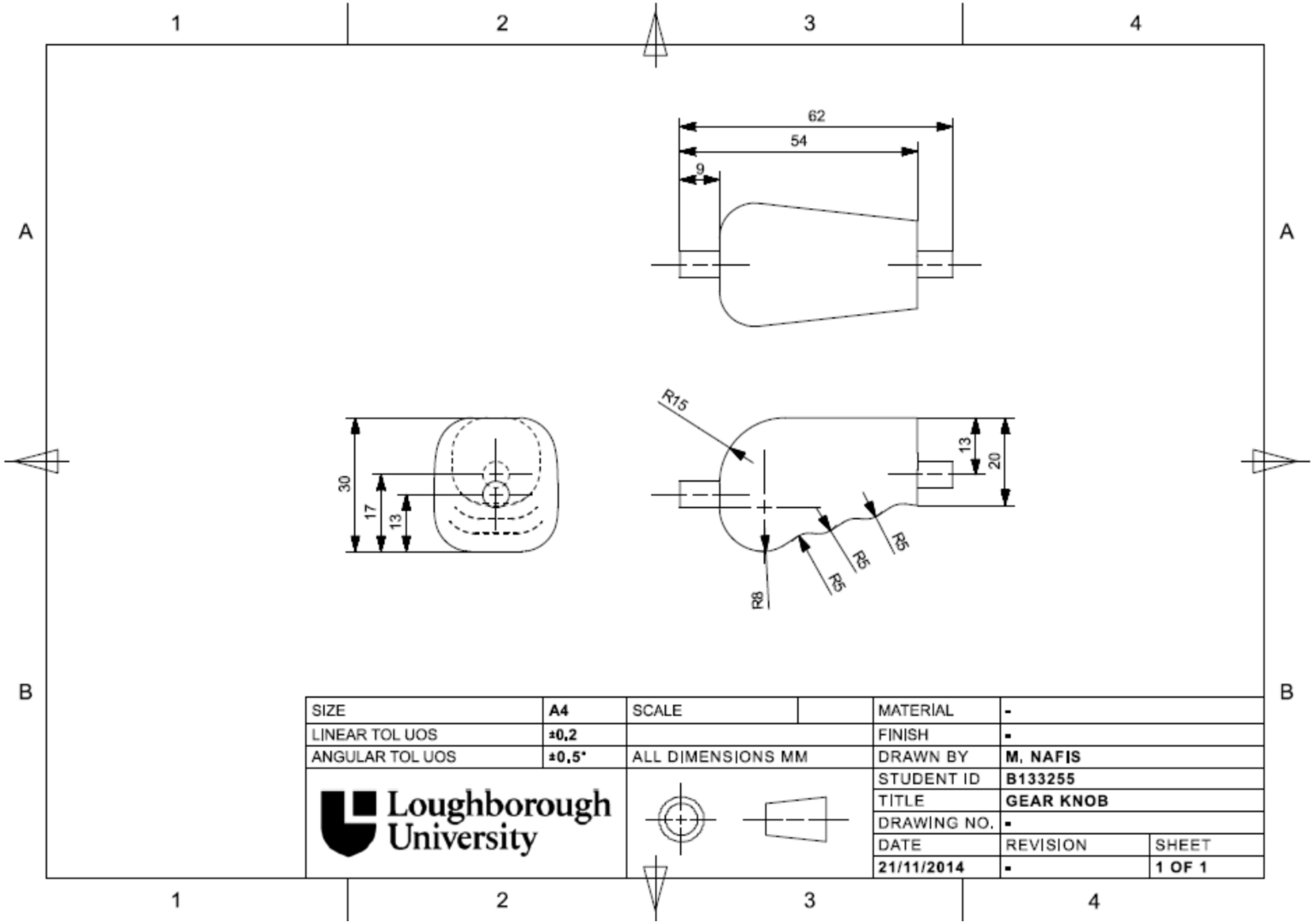
				DATE	REVISION	SHEET
				21/11/2014	-	**1 OF 1**

CAD PART: Ceane hook



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Loughborough University				STUDENT ID	B133255
				TITLE	GEAR KNOB
				DRAWING NO.	-
				DATE	REVISION / SHEET
				21/11/2014	- / 1 OF 1

Appendix C:

Functional code to select the part body

```
Function SelectBody(ByVal prompt As String, ByRef selObj() As NXObject) As
Selection.Response

        Dim theUI As UI = UI.GetUI
        Dim title As String = "Select Part, Blank & Check"
        Dim includeFeatures As Boolean = False
        Dim keepHighlighted As Boolean = False
        Dim selAction As Selection.SelectionAction =
Selection.SelectionAction.ClearAndEnableSpecific
        Dim scope As Selection.SelectionScope =
Selection.SelectionScope.WorkPart
        Dim selectionMask_array(0) As Selection.MaskTriple

        With selectionMask_array(0)
            .Type = UFConstants.UF_solid_type
            .SolidBodySubtype = UFConstants.UF_UI_SEL_FEATURE_BODY
        End With

        Dim resp As Selection.Response =
theUI.SelectionManager.SelectObjects(prompt, _
         title, scope, selAction, _
         includeFeatures, keepHighlighted, selectionMask_array, _
         selObj)
        If resp = Selection.Response.Ok Then
            Return Selection.Response.Ok
        Else
            Return Selection.Response.Cancel
        End If
    End Function
```

Appendix D:

Functional code to select cutting areas

```
Function SelectCuttingAreas(ByVal prompt As String, ByRef selObj() As
NXObject) As Selection.Response

        Dim theUI As UI = UI.GetUI
        Dim title As String = "Select faces"
        Dim includeFeatures As Boolean = False
        Dim keepHighlighted As Boolean = False
        Dim selAction As Selection.SelectionAction =
Selection.SelectionAction.ClearAndEnableSpecific
```

```
        Dim scope As Selection.SelectionScope =
Selection.SelectionScope.WorkPart
        Dim selectionMask_array(0) As Selection.MaskTriple

        With selectionMask_array(0)
            .Type = UFConstants.UF_solid_type
            .SolidBodySubtype = UFConstants.UF_UI_SEL_FEATURE_ANY_FACE
        End With

        Dim resp As Selection.Response =
theUI.SelectionManager.SelectObjects(prompt, _
         title, scope, selAction, _
         includeFeatures, keepHighlighted, selectionMask_array, _
         selObj)
        If resp = Selection.Response.Ok Then
            Return Selection.Response.Ok
        Else
            Return Selection.Response.Cancel
        End If

    End Function
```

Appendix E:

Codes to record machining time and export the data to excel file

```
Dim theUI As UI = UI.GetUI()
Dim dispPart As Part = theSession.Parts.Display
Dim lw As ListingWindow = theSession.ListingWindow
lw.Open()
  Try
    totalMachineTime = 0
    Dim machineTimeSpan As TimeSpan
    Dim strHeader As String = "name, toolpath time"
    Dim opers As OperationCollection =
dispPart.CAMSetup.CAMOperationCollection
    For Each oper As Operation In opers
       totalMachineTime += oper.GetToolpathTime
       Dim strOperation As String = ""
       strOperation &= oper.Name & ","
       strOperation &= oper.GetToolpathTime.ToString
Next
machineTimeSpan = TimeSpan.FromSeconds(totalMachineTime)
Catch ex As NXOpen.NXException
UI.GetUI().NXMessageBox.Show("Message", NXMessageBox.DialogType.[Error],
ex.Message)
Catch ex As Exception
UI.GetUI().NXMessageBox.Show("Message", NXMessageBox.DialogType.[Error],
ex.Message)

End Try
End Sub
```

```
Sub WriteValueToExcel(ByVal myData(,) As Double, ByVal iCount As Integer)

Dim oExcel = CreateObject("Excel.Application")
   If oExcel Is Nothing Then
   MsgBox("Failed to start Excel")
   Return
   End If

Dim oBook As Object
Dim oSheet As Object

   Try
     oBook = oExcel.Workbooks.Add
     oSheet = oBook.Worksheets(1)

     For i As Integer = 1 To iCount
         oSheet.Cells(i, 1).Value = myData(i, 1)
         oSheet.Cells(i, 2).Value = myData(i, 2)
     Next
         oExcel.Visible = True
         Catch ex As Exception
         MsgBox(ex.GetType.ToString & " : " & ex.Message, MsgBoxStyle.OkOnly,
         "Error")
         oBook = Nothing
         oSheet = Nothing
         oExcel.quit()
         oExcel = Nothing

End Try
End Sub
```

Appendix F:

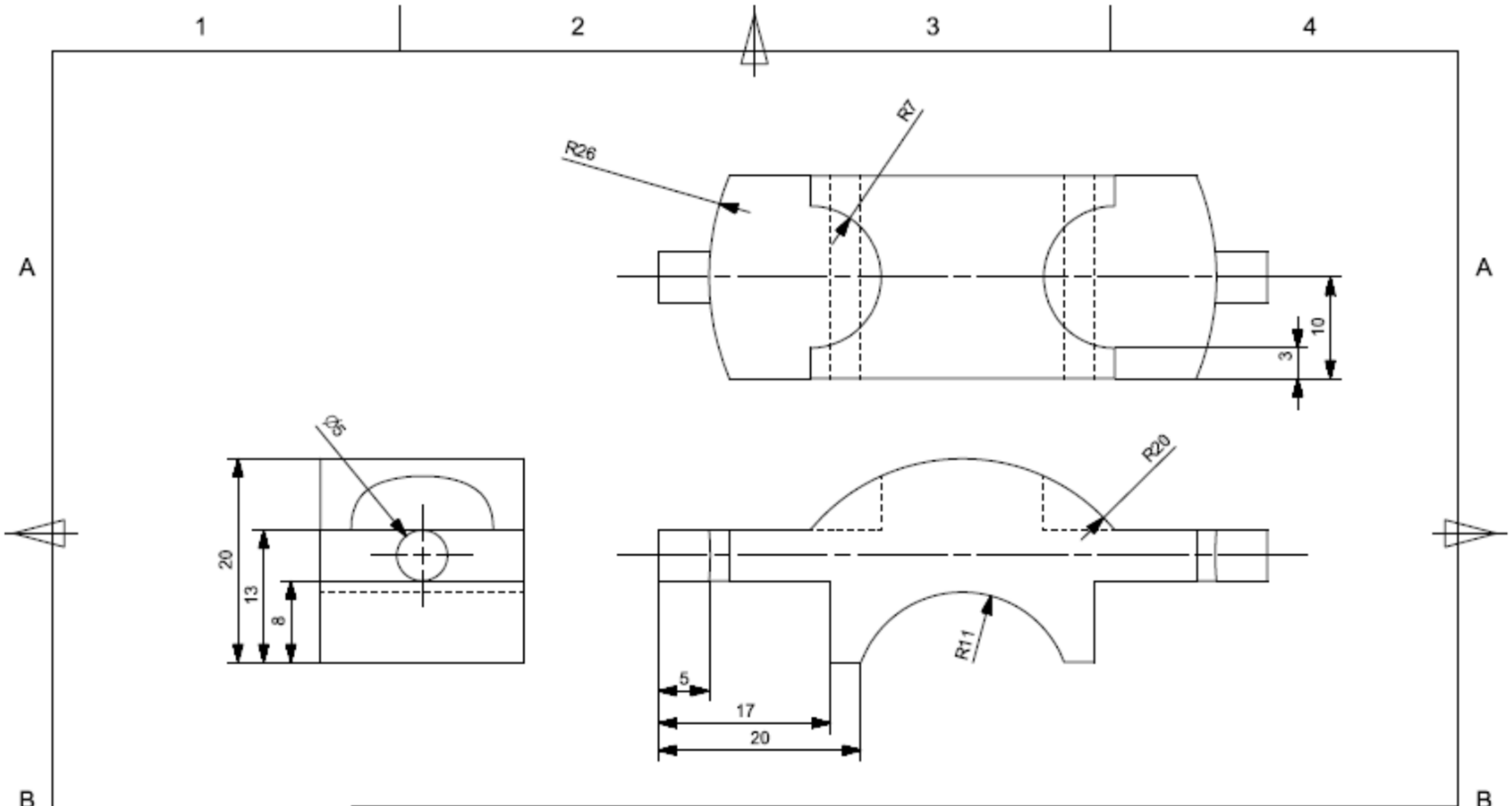
Functional code for flat and non-flat surfaces

```
Function SelectFlatSurfaces1(ByVal prompt As String, ByRef selObj() As
NXObject) As Selection.Response

        Dim theUI As UI = UI.GetUI
        Dim title As String = "Orientation 2: Select Flat Surfaces"
        Dim includeFeatures As Boolean = False
        Dim keepHighlighted As Boolean = False
        Dim selAction As Selection.SelectionAction =
        Selection.SelectionAction.ClearAndEnableSpecific
        Dim scope As Selection.SelectionScope =
Selection.SelectionScope.WorkPart
        Dim selectionMask_array(0) As Selection.MaskTriple

        With selectionMask_array(0)
            .Type = UFConstants.UF_solid_type
            .SolidBodySubtype = UFConstants.UF_UI_SEL_FEATURE_PLANAR_FACE
        End With
```

```
        Dim resp As Selection.Response =
        theUI.SelectionManager.SelectObjects(prompt, _
        title, scope, selAction, _
        includeFeatures, keepHighlighted, selectionMask_array, _
        selObj)
        If resp = Selection.Response.Ok Then
            Return Selection.Response.Ok
        Else
            Return Selection.Response.Cancel
        End If
End Function



Function SelectNonflatSurfaces1(ByVal prompt As String, ByRef selObj() As
NXObject) As Selection.Response

        Dim theUI As UI = UI.GetUI
        Dim title As String = "Orientations 1: Select non-flat surfaces"
        Dim includeFeatures As Boolean = False
        Dim keepHighlighted As Boolean = False
        Dim selAction As Selection.SelectionAction =
        Selection.SelectionAction.ClearAndEnableSpecific
        Dim scope As Selection.SelectionScope =
Selection.SelectionScope.WorkPart
        Dim selectionMask_array(0) As Selection.MaskTriple

        With selectionMask_array(0)
            .Type = UFConstants.UF_solid_type
            .SolidBodySubtype = UFConstants.UF_UI_SEL_FEATURE_ANY_FACE
        End With

        Dim resp As Selection.Response =
        theUI.SelectionManager.SelectObjects(prompt, _
        title, scope, selAction, _
        includeFeatures, keepHighlighted, selectionMask_array, _
        selObj)
        If resp = Selection.Response.Ok Then
            Return Selection.Response.Ok
        Else
            Return Selection.Response.Cancel
        End If
End Function
```

Appendix G:

Dimensional sketches for mechanical component, propeller, prop mount, shampoo bottle, toothbrush handle, earphone and femur bone



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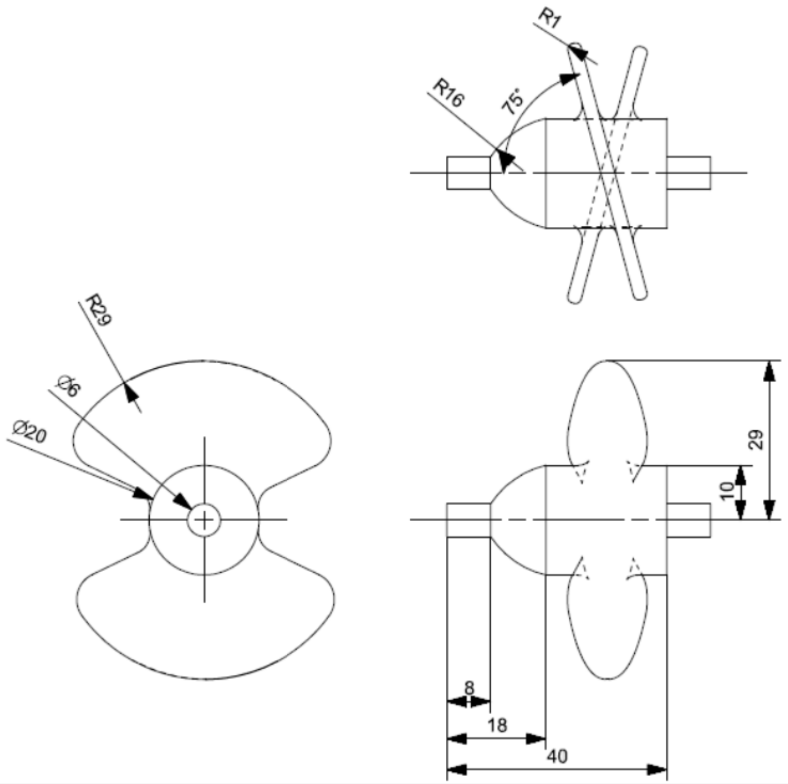

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Loughborough University				STUDENT ID	B133255
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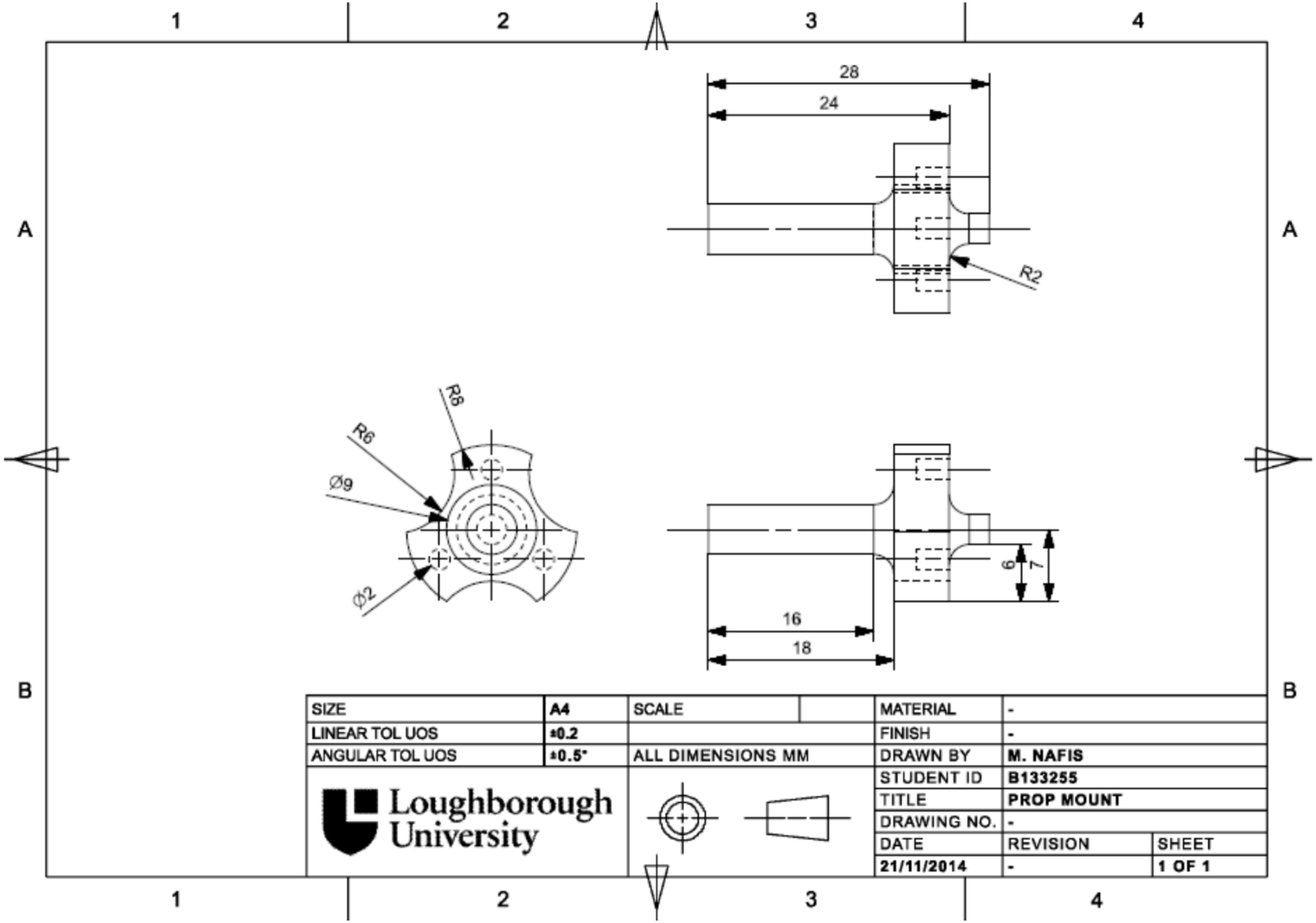
				DATE	REVISION / SHEET
				21/11/2014	- / 1 OF 1



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Loughborough University				STUDENT ID	**B133255**	
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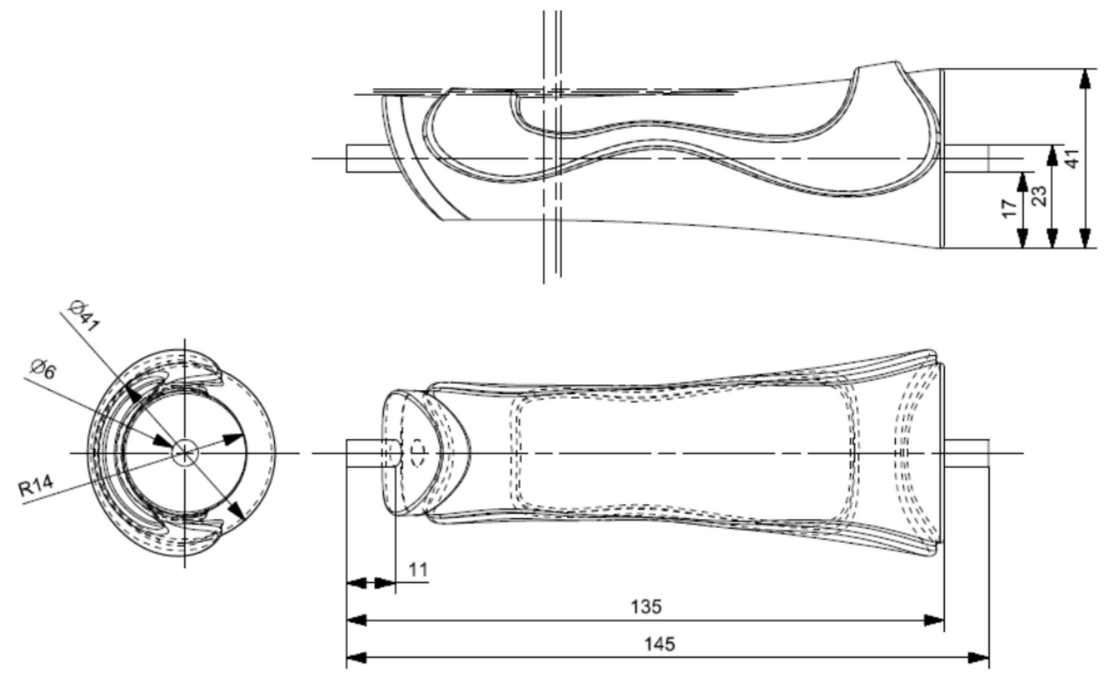

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ANGULAR TOL UOS	±0.5°	ALL DIMENSIONS MM		DRAWN BY	M. NAFIS	
Loughborough University				STUDENT ID	B133255	
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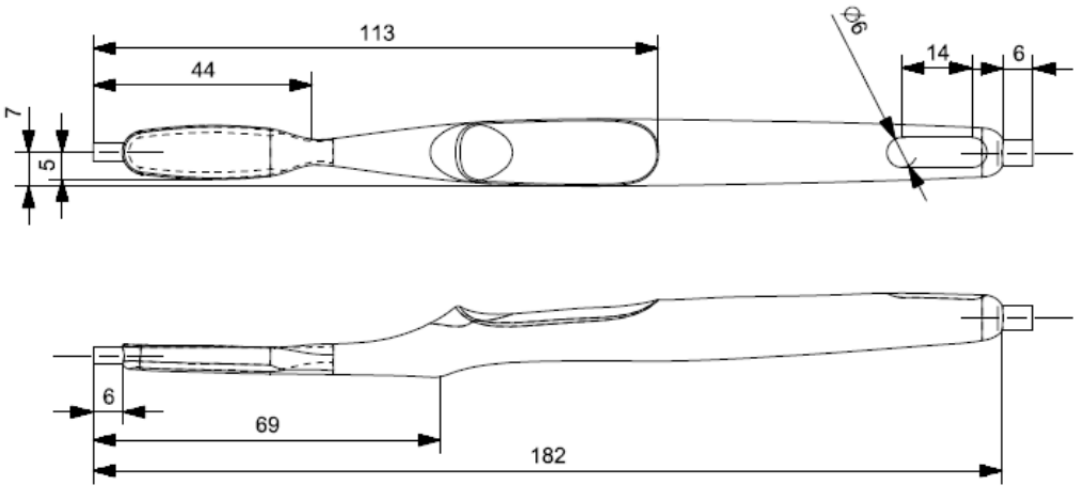
				DRAWING NO.	-	
				DATE	REVISION	SHEET
				21/11/2014	-	1 OF 1



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Loughborough University				STUDENT ID	**B133255**	
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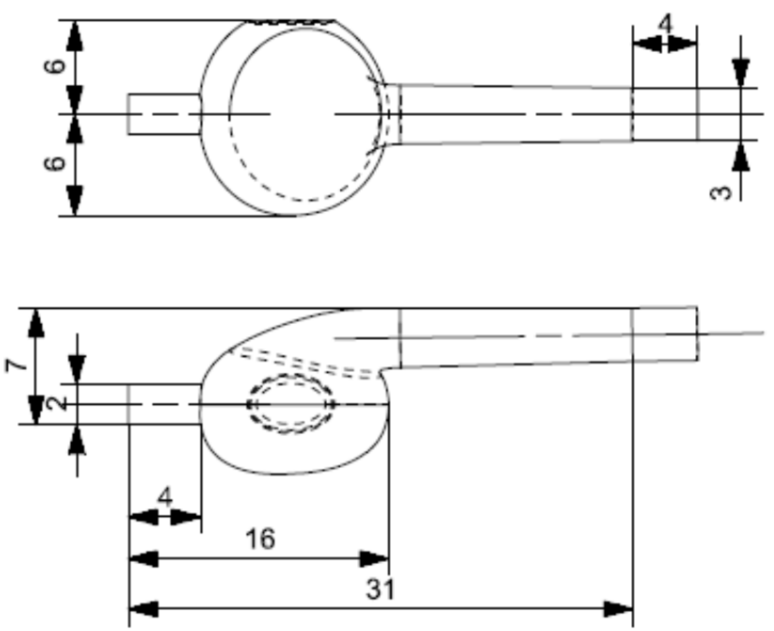

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Loughborough University				STUDENT ID	B133255	
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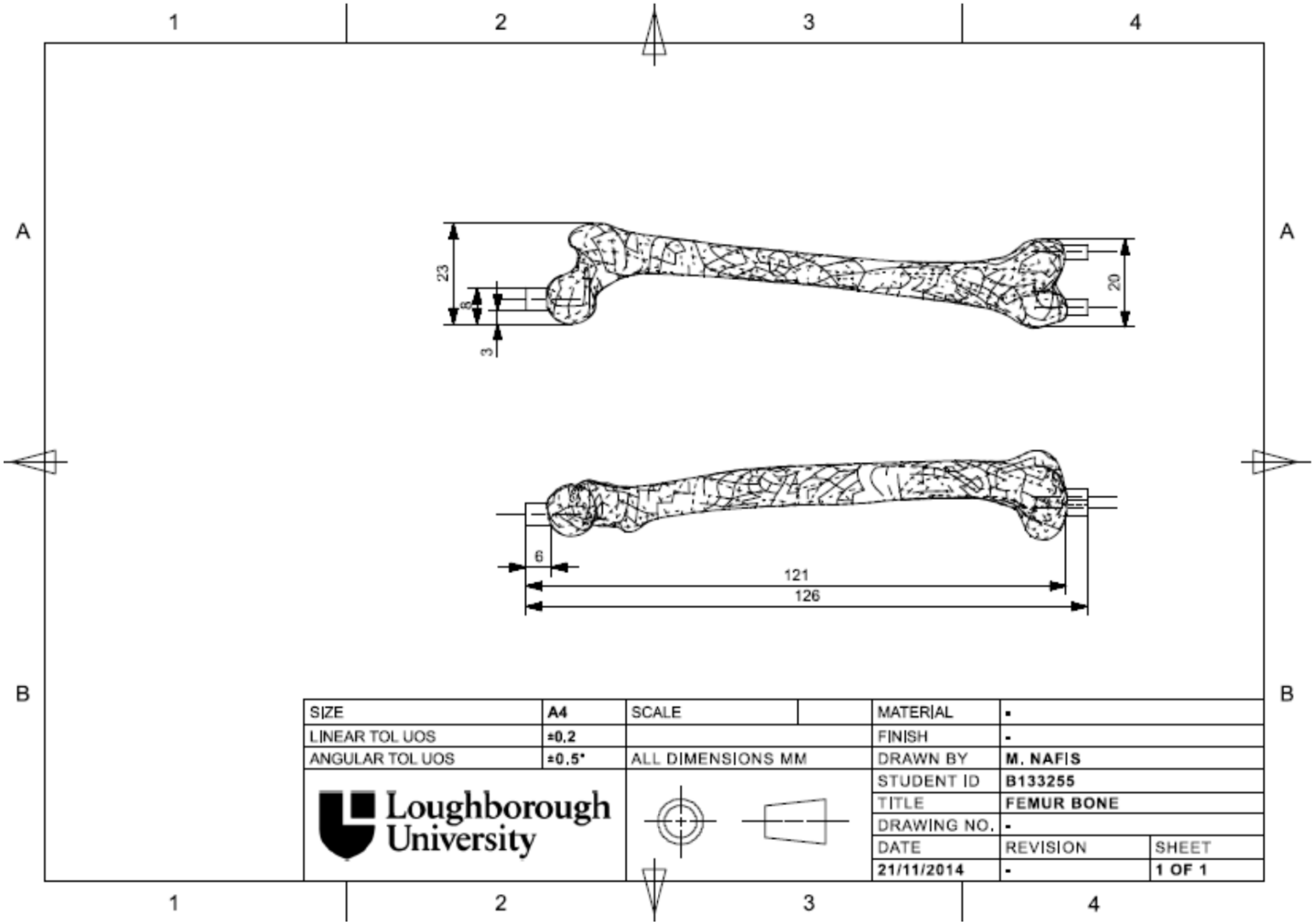

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ANGULAR TOL UOS	±0,5°	ALL DIMENSIONS MM	

Loughborough University

MATERIAL	-	
FINISH	-	
DRAWN BY	M. NAFIS	
STUDENT ID	B133255	
TITLE	FEMUR BONE	
DRAWING NO.	-	
DATE	REVISION	SHEET
21/11/2014	-	1 OF 1