

**4 AXIS MACHINING SIMULATION ROUTINES
VIA APPLICATION PROGRAMMING
INTERFACE (API) IN CAM SYSTEMS**

MOHAMAD HAFIZ BIN MOHAMAD

MASTER OF SCIENCE

UNIVERSITI MALAYSIA PAHANG

UNIVERSITI MALAYSIA PAHANG

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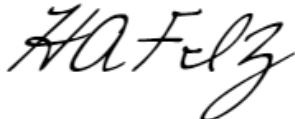
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ID Number : MMF16003

Date : 03 MARCH 2021

**4 AXIS MACHINING SIMULATION ROUTINES VIA APPLICATION
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MOHAMAD HAFIZ BIN MOHAMAD

Thesis submitted in fulfilment of the requirements
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ABSTRAK

Kebanyakan sistem Computer-Aided Manufacturing (CAM) dilengkapi dengan alat simulasi bagi tujuan pengesahan program permesinan. Di dalam perancangan proses permesinan, simulasi adalah suatu elemen yang penting untuk mencapai output yang berkualiti dan keputusan simulasi yang tepat. Pemilihan parameter yang optimum akan menghasilkan operasi permesinan yang berkesan dengan masa yang minimum dan memperoleh kualiti produk yang baik. Walaubagaimanapun, operasi simulasi di dalam sistem CAM kadangkala menjadi kurang efisien, terutamanya apabila melibatkan proses yang berulang di mana memerlukan beberapa input yang berkemungkinan untuk dianalisis. Intervensi manual daripada manusia juga masih diperlukan untuk penyediaan simulasi pemesinan. Objektif kajian ini adalah untuk mengkaji perlaksanaan paparan pengaturcaraan untuk mengendalikan simulasi permesinan di dalam sistem CAM. Kajian ini memberi penumpuan khusus kepada korelasi antara beberapa kaedah pemotongan kepada kecekapan permesinan terutamanya di dalam permesinan 4-paksi. Aplikasi yang dinamakan RoughSimulCAM dan FinishSimulCAM telah dibangunkan dalam penyelidikan ini untuk membantu rutin simulasi di dalam paparan CAM. Pada dasarnya, pembangunan ini melibatkan penterjemahan arahan simulasi dari sistem CAM ke dalam bahasa pengaturcaraan. Pada peringkat ini, kod diubahsuai, dipertingkatkan dan disesuaikan untuk membantu rutin simulasi permesinan. Fungsi utama pembangunan aplikasi ini adalah untuk mensimulasikan beberapa siri operasi permesinan berdasarkan data input yang berubah-ubah dan menghasilkan parameter yang optimum bagi proses permesinan. Aplikasi ini diprogramkan semula di dalam Visual Basic 10 dan disepadukan di dalam sistem NX CAM 10. Ia berfungsi pada dua peringkat yang berbeza, iaitu operasi Roughing dan operasi Finishing. Parameter pemotongan yang dinilai di dalam operasi Roughing adalah orientasi pemotongan, manakala di dalam operasi Finishing adalah parameter Axial Depth-of-cut dan Radial Depth-of-cut. Aplikasi RoughSimulCAM menganalisis operasi Roughing melalui pemanipulasi orientasi pemotongan yang berbeza-beza dan menjana anggaran jumlah isipadu yang dipotong. Set orientasi yang memotong jumlah isipadu bahan yang tertinggi dipilih sebagai parameter yang optimum dan akan digunakan untuk melaksanakan operasi Roughing. FinishSimulCAM berfungsi untuk mewujudkan korelasi yang optimum antara parameter Axial Depth-of-cut (ADOC) dan parameter Radial Depth-of-cut (RDOC). Satu set ADOC dan RDOC dengan pengurangan isipadu tertinggi akan dicadangkan pada akhir simulasi. Parameter ini sangat bergantung pada ciri-ciri geometri yang ditunjukkan pada bahagian model yang dimesin. Beberapa operasi pemesinan dilakukan dalam permesinan 4 paksi untuk mengesahkan program ini. Penyelidikan ini adalah sebahagian daripada usaha untuk mewujudkan kaedah yang efisien dalam melakukan rutin simulasi untuk mesin CNC. Pada akhirnya, kaedah yang dicadangkan dalam penyelidikan ini berjaya menambahbaik masa pemprosesan simulasi pemesinan keseluruhan hingga 77.3%, iaitu dari 22.50 min hingga 5.11 min setiap operasi. Dari segi prestasi kekasaran permukaan, hasil keseluruhan yang dicapai untuk setiap simulasi di bawah $1.0 \mu\text{m}$, ianya masih dapat diterima bagi operasi permesinan “finishing” dengan manual penggilapan. Implikasi yang dapat dilihat dari kajian ini ialah, mampu meminimumkan tugas-tugas perancangan proses permesinan, mampu memperluaskan keupayaan CADCAM untuk mensimulasikan berbagai pendekatan pemotongan dan berhasil memperolehi kualiti permesinan yang baik.

ABSTRACT

Most of the Computer-Aided Manufacturing (CAM) systems were built-in with the simulation tools for validation purposes. In machining process planning, simulation has become an important element to achieve reliable output and obtain efficient result. Proper selection of optimum machining parameters will allow effective cutting operation with minimum time and good product quality. However, the simulation tasks in CAM system can become inefficient especially for the repeating routines that required various possibility input to the analysis. Manual human interventions are still needed for machining simulation setup. The objective of this research is to investigate the implementation of programming interface in CAM systems to handle simulation routines. The research is specifically focus on the correlation of several cutting approaches towards machining efficiency particularly in 4 axis milling machining. The applications namely as RoughSimulCAM and FinishSimulCAM were developed to assist the simulation routines in CAM interface. Basically, the development involves translating the simulation instructions in CAM into programming language. From this point, the codes are modified, enhanced and customized to assist the simulation routines. The functions of the developed applications are to simulate series of machining operations based on variable input data and generate optimum parameters for cutting processes. These applications are programmed in Visual Basic 10 and integrated within NX CAM 10 system. The applications work on two different stages of cutting which are roughing and finishing operations. The cutting parameter evaluated in roughing operations is cutting orientation, while in finishing operation, the axial and radial depth-of-cut is studied. RoughSimulCAM analyzes roughing operation through the manipulation of different cutting orientation and generate estimated volume removed. Orientations set with highest volume remove is selected as optimum parameter to execute roughing operations. FinishSimulCAM works to establish optimum correlation between axial depth-of-cut (ADOC) and radial depth-of-cut (RDOC). A set of ADOC and RDOC with highest volume remove will be proposed at the end of the simulation. This parameter is highly depending on the geometrical features presented on machined part. Series of machining operations were carried out in 4 axis CNC milling machine setup to validate the program. This research is part of an attempt to establish efficient method in performing the simulation routines for CNC machining. Ultimately, the method proposed in this research manages to improve overall machining simulation processing times up to 77.3%, which is from 22.50 min to 5.11 min per operation. In terms of surface roughness performances, overall results achieve for each simulation are below than 1.0 μm , which is acceptable for finishing operation with manual polishing. The implications can be perceived from this study is capable to minimized of process planning tasks, expanded the CAD/CAM ability to simulate various cutting approaches and managed to obtain acceptable quality of machined parts.

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LIST OF SYMBOLS

°	Angle
%	Percentages
Ra	Arithmetic Mean Deviation (Roughness)
mm	Millimetre
mm ²	Square Millimetre
mm ³	Cubic Millimetre
µm	Micrometre
°	Angle
%	Percentages
Ra	Arithmetic Mean Deviation (Roughness)
mm	Millimetre
mm ²	Square Millimetre

LIST OF ABBREVIATIONS

ADOC	Axial Depth of Cut
API	Application Programming Interfaces
CAD	Computer Aided-Design
CAE	Computer Aided Engineering
CAM	Computer Aided-Manufacturing
CAPP	Computer Aided Process Planning
Ch	Cusp Height
CLSF	Cutter Location Source Files
CNC	Computer Numerical Control
C-Space	Configuration Space
DOE	Design of Experiment
F	Flat
GPU	Graphical Processing Unit
GRIP	Graphical Interactive Programming
GUI	Graphical User Interfaces
KF	Knowledge Fusion
MPP	Manual Process Planning
MPP	Machining Process Planning
MRR	Material Removal Rate
NC	Numerical Control
NF	Non-Flat
NX	NX CAM Software
RDOC	Radial Depth of Cut
RM	Rapid Machining
RP	Rapid Prototyping
RPM	Revolution per Minutes
RSM	Response Surface Method
SNAP	Simple NX Application Programming
SR	Surface Roughness
VBA	Visual Basic Application
VM	Virtual Manufacturing

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CHAPTER 1

INTRODUCTION

1.1 Research Overview

The development and incorporation of programming codes into Computer Numerical Control (CNC) system are applicable to satisfy the requirement of industrial demand for process planning management. CNC is a system that consist of integration between computers with the machine (on-board computer) (Kalpakjian and Schmid, 2006). It has capability to prepare, generate, modify and store machining programs for different parts. Nowadays, CNC systems are widely used in industry due to capability of program-editing, large memory in small computer and low-cost programmability. It is an important element which contributed to the advancement in the Computer-Aided Manufacturing (CAM) field. CAM is a system which involves the use of numerical control programming to assist manufacturing engineer in all phases of product manufacturing (Kalpakjian and Schmid, 2006). CAM has an ability to link the modern computer to material processing of CNC machines (Krar, Gill, & Smid, 2005). Historically, in 1950s, most of typical plant in manufacturing operations applied traditional machinery. This practice is nearly lack of flexibility and unpractical, where required a skilled operator to handle the operation and produce a part according to characteristic needed. The machinery, fixtures and material had to be rearranged every time to produce different products. A number of trial-and-error was attempted manually by the operator to find out the optimum parameters for machining processes particularly for a new parts or product. Therefore, to manufacture actual parts as same as virtual parts is seems unreliable, costly and time consuming (Kalpakjian and Schmid, 2006) . In order to bring up the product into global market, it is important to ensure that the product is manufactured within timeframe according to the demand order. Hence, the necessity for reducing the production time and manufacturing cost became increasingly important. The flexibility and efficiency of manufacturing and process planning also need to be improved.

1.2 Problem Statements

The advancement of CAD/CAM technology has permitted various simulation routines to be carried out. In machining processes, common simulation routines mainly involved the optimization of cutting parameters and cutting visualization. The nature of machining simulation involves several parameter values to be set and changed whilst maintaining the uniformity of the process without interruptions. Hence, machining simulation required a lot of set up and highly dependent to the user of the system. Recent development in CAD/CAM system has enhanced the simulation routines where it tends to employ Rapid Prototyping concept which certain level of automation (Nafis, Case, & Watts, 2017). However, there are still rooms for improvement in terms of simulation method and process efficiency. This can be seen from two points of view that relate to the empirical relationship between input and output parameter and the designation of simulation process planning. Basically, CNC milling is divided into two operations, roughing and finishing. Roughing operation task is mainly executing to remove a large amount of workpiece volume, where finishing operation used to refine the shapes of the workpiece according to the dimensions set in the part drawing. It is normal practices to validate the CNC machining operation virtually in CAD/CAM systems before execute real process. Basically, most of CAD/CAM systems are equipped with tools to simulate different kinds of machining operations and also capable to generate NC program. In recent years, the capability of the CAD/CAM system has been expanded to adapt with various machining simulation and capable to handle complex process optimization. Its allows the system to check the functionality and reliability of the NC program with reflection towards the process ability in real CNC machining (Klimant, Witt, & Kuhl, 2014). Main focus of the CAD/CAM development are to guarantees the quality and efficiency of the process, minimizing machining time, cost saving and improve the productivity (Kadir & Xu, 2011).

Nowadays, most of the CAD/CAM systems are equipped with the machining simulation tool. It has become an important element in process planning and provides reliable solutions in obtaining efficient cutting operations. Moreover, it has a major influence of processing time and cost during production stage. However, in 4 axis milling machining, manual interventions are still required to setup the machining

simulation and this is time consuming especially when dealing with the repetitive operations. For example, the cutting process with indexing devices required the simulation setup being repeated whenever there is a changes in cutting angles of the indexer. In order to search for optimum angle, the process will consume a lot of time to change the angle values and restart the simulation. This caused the simulation process becomes non-productive and need to be optimized. Thus, the applicability of the systems is slightly inefficient and constrained. In 4 axis machining processes, the time taken to develop process planning and produce optimum cutting parameter can be easily absorbed over a long period. While many efforts, the preparation on the machining process remains a bottle-neck during automated manufacturing processes (Klancnik, Brezocnik, & Balic, 2016). Based on previous analysis, manual process planning is a common method that are used in industry, in terms of process planning automation, standardization input, systematic data and information management (Anderberg, Beno, & Pejryd, 2009). The dependency on experienced experts is still high for the operation setup and parameters selection. This research attempts to embed middle level of automation in 4 axis milling machining simulation program and improve the process planning in CAD/CAM system by focusing on repetitive operational.

In most cases, the available CAD/CAM systems are only capable to deal with standard simulation routines and restricted by the available built-in function in the system. The applicability to expand and develop custom simulation routines that suit with the user requirement is limited. In order to simulate for process optimization, the establishment of empirical relationship between input and output parameter is a crucial and need to be investigated to ensure the machining operation is successful (Yusup, Mohd, Zaiton, & Hashim, 2012). The chosen process parameters are depending on the predicted response parameters. For example, to predict the value of Surface Roughness (SR) and Material Removal Rate (MRR), an input parameters to be evaluates are spindle speed (rpm), feed rate (mm/min) and depth of cut (mm) (Raut & Shinde, 2015). For the optimization, a set of value for input parameter is simulated continuously until an optimum result is obtained. Unfortunately, the standard CAD/CAM system still not been able to simulate operations with a few inputs, unless with additional effort to execute the processes manually. Hence, based on the stated concerns, a customized machining simulation program can be considered as a reliable solution to expand the

applicability of machining simulation routines in CAD/CAM system. Figure 1.1 illustrates the research problem statement and possible solutions.

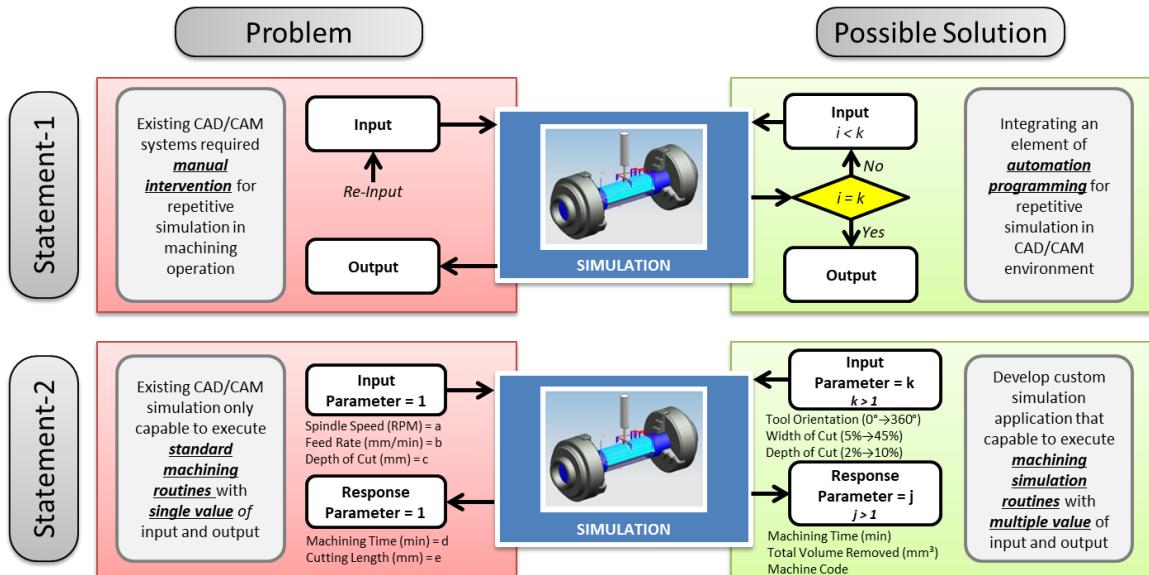


Figure 1.1 Research problem statement and possible solution

The general overview of this research is to investigate the simulation approaches for 4 axis milling machining routines in CAM system. The need for process automation is identified and transformed into a research questions as follows:

How to improve the simulation routines for 4 axis milling machining processes with available tools in current CAD/CAM system?

Table 1.1 has shown the work progression of this research. The first and second question is the initial point of the research where the aim is to formulate a better frame of machining simulation from 4 axis machining perspective with a focus on process planning. The third question is important for establishing machining simulation processes that minimize the time by integrating the automation element in CAM systems.

Table 1.1 Research questions and rationales

RESEARCH QUESTIONS	RATIONALE
What are the simulation routines deficiencies in the machining processes?	This is the main point and research aim in order to describe the situation in 4 axis machining simulation routines
How extensive the current CAM system can be used in machining simulation?	Initially it is based on a broader approach to the machining process in CAM, and then the scope was subsequently narrowed to a more in-depth understanding of particular CAM system process simulation approach
How to ensure the improved CAM simulation methodology decrease human intervention and embed automation element in the process planning?	In order to adopt automation level in CNC machining simulation routines, a new approach will be introduced by incorporating programming instructions in CAM systems. The integration of programming code into standard CAM systems is an extensive approach to broaden the applications.

1.3 Research Objectives

Based on the literature, there are two approaches that can be adopted to improve machining simulation routines. The first approach consists of optimizing the method of machining simulation to improve process planning. The improvement in the simulation are expected to enhance the process capability. It permits the execution of different kinds of simulation such as cutting orientation and cutting parameter. There are many approaches and methodology that have been studied by previous researcher to perform the machining simulation and optimization in metal cutting operation (Y. Zhang, Xu, & Liu, 2011) (Deepak, 2012) (Matta, Ranga Raju, & Suman, 2015). In 4 axis machining, cutting orientation and parameters in roughing and finishing operation are among the factors contributes to the machining time and machined parts quality. The second approach focuses on the automation elements while simulating the cutting parameters in CAM systems. Virtual setup in CAM system allows the machining operator to input predetermined parameter value before execute the simulation. However, in most cases, the simulation need at least three to ten or more set of parameter to identify optimum combination. This cause the simulation routine need to be repeated at certain cycles. The experience of the machining operator is crucial to maintain of the degree of accuracy in terms of input precision (Scallan, 2002). Therefore, due to that requirement,

it is necessary to develop a system with capable to cater multi-predetermined input. Machining sequences and parameter designation will be managed by the systems. The system then will execute a simulation once it received multi-predetermined input from the user. So far, however, there are only few research make an effort to enhance the automation level in machining simulation based on multi-predetermined input. This approach can be considered as an alternative way to shorten the machining lead time. The integration of programming code is required to extend the level of automation in CAM systems and enhance the adaptability to any machining operation and scenario.

The first research objective is to study the implementation of programming codes in CAM systems by developing a customized program to perform the simulation processes. The main topics to achieve in this objective is to identify potential function of Application Programming Interfaces (API) to be automated in NX CAM system. Next step is to develop customized Graphical User Interface (GUI) with integration of decision making tool to assist user to generate machining operation. Finally, to evaluate the performance of the developed approach with conventional method in terms of processing step and time.

The second research objective is to analyse the applicability of the developed program in simulating 4 axis machining operations using non-complex CAD models. The crucial task is mainly to develop a roughing simulation machining operation by simulate various cutting angles with different sets of orientations. This followed by the development of a finishing simulation machining operation by correlating cutting parameters between radial depth-of-cut (RDOC) and axial depth-of-cut (ADOC). The results will be analysed by evaluating the effects of machining simulation on total volume removed.

The third research objective is to further validate the approach through machining operation based on the optimum results obtained in simulation study. The machining is carry out using 4 axis milling machine with aluminium as workpieces material. The experiment outcomes are evaluated in terms of the accuracy of volume removed and quality of surface roughness.

1.4 Research Scopes

The scope of the research is outlined as below:

- The research focuses on 4 axis CNC milling operations,
- The machining processes are conducted by using conventional 3-axis CNC machine with attachable 1-axis indexer devices.
- The applications used in this research are Siemens NX CAM 10 system and Microsoft Visual Basic Studio 10.
- The investigations of input parameters are based on cutting orientation, radial depth of cut (RDOC) and axial depth of cut (ADOC).
- The response parameters and evaluation on machining performance are focuses on total volume removed, machined parts accuracy and surface finished.

1.5 Research Framework

An overview of the research framework is outlined in Figure 1.2. The first part of this research is a review of the literature as presented in chapter 2. The subsequent parts include the development of the proposed simulation, improvement of roughing operation, and improvement of finishing operation, validate the simulation programme virtually in NX CAM software and experimentally test the efficiency of developed applications using 4 axis machining operation.

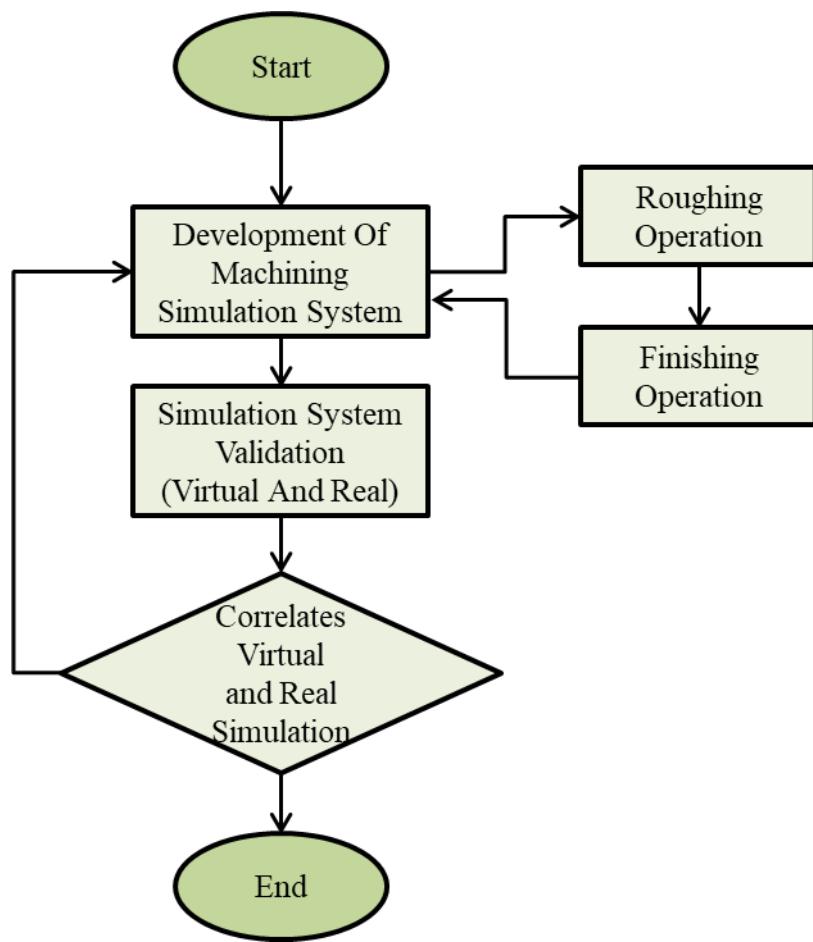


Figure 1.2 Research framework

1.6 Thesis Organization

This thesis explained on how machining simulation routines can be optimized and helps the user to simulate and analyst the machining performance based on minimum processing step and time. A summary of the thesis has been organized in the following flows:

Chapter 1: This chapter explains a brief view of research background, problem statement, research questions, research objectives and research scopes.

Chapter 2: This chapter covers the literature review. It started with an introduction to machining processes in manufacturing sectors. Then next sub-chapter continues with CNC machining technology processes which explained the general terminology of machining and NC parts programming. The discussion continues with the explanation of process planning in CNC machining, manual process planning (MPP) and computer-aided process planning (CAPP). In the next sub-chapter, discussions about simulation routines in CNC machining have been reviewed in detail based on previous work from other researchers. The discussions include machining orientation simulation for roughing operation and machining parameter simulation for finishing operations. Based on the review, a new approach is formulated to be undertaken in this study. Basically, the basis of the development relied on the previous works but with slight improvement in term of methodology and adaptability. This chapter ends with a discussion on the integration and adaptability of programming applications in CAD/CAM software to further enhance the capabilities in executing virtual machine operations and simulations.

Chapter 3: This chapter presents the research methodology. The chapter was divided into three main sub-chapter, Development of Simulation Program, Machining Simulation and Machining experiment. The first sub-chapter provides a brief description on the development of simulation programs and graphical user interfaces (GUI), which is used as atoll to execute machining simulation and operations. Two different programs consist of roughing and finishing were developed, where each program executes different simulation approaches. Through the developed simulation programs, the performances of machining operations for roughing and finishing can be measured within minimum processing steps. The procedures and methods used in

development process to build the machining simulations program are also discussed. Next sub-chapter presents the methodology to execute a simulation analysis for machining operation. In roughing operation, a method to execute multiple cutting orientation simulation was presented. In finishing operation, a method to execute multi depth of cut correlation simulation is proposed. The methodology for machining simulation was discussed including the process planning and verification methods. The results of machining simulation were discussed in details and a summary was described at the end of the chapter.

Chapter 4: This chapter presents the results and discussion of the machining simulations. The chapter was divided into two sub-chapter consist of Simulation Results and Machining (Experiment) Results. The simulation results represent the results of simulation for roughing and finishing operation by using developed program within NX CAM and Vericut software. The analysis is focused on the highest volume removed for each tested model. The second sub-chapter is the results of machining (experiment) simulation. Real machining experiment is carried out to validate the practicality of developed simulation software. After completing the machining, volume and weight assessment are verified followed by roughness analysis on the machined parts surfaces.

Chapter 5: This chapter summarizes the works contained to establish the research. The findings are reflecting back to the research objectives and discussed along with the suggestions for future works.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Machining simulation is the key of revolution to improve the productivity and quality of the finished product. The different machining strategies are able to be analysed by using simulation approach without any damage or waste on the material sources (Valvo, Licari, & Adornetto, 2012). It is an important procedure to pre-evaluate the machining in virtual environment, before proceed into real machining. A computer based technology for machining simulation is well known as Virtual Manufacturing (VM). Virtual manufacturing is a systems which have a capability to optimize the production activities and improve the production efficiency via simulation prior to the actual production (J. G. Li, Zhao, Yao, & Liu, 2008). Virtual machining is considered as a part of machining processes. The concepts of virtual machining are purposely to pre-evaluate actual machining trials by simulating the machining processes in digital environment. The simulation routines are executed in CAM software where if the faulty is found, the simulation is repeated until a satisfactory output is obtained (Altintas et al., 2014). The architecture of a virtual machining system is illustrated in Figure 2.1.

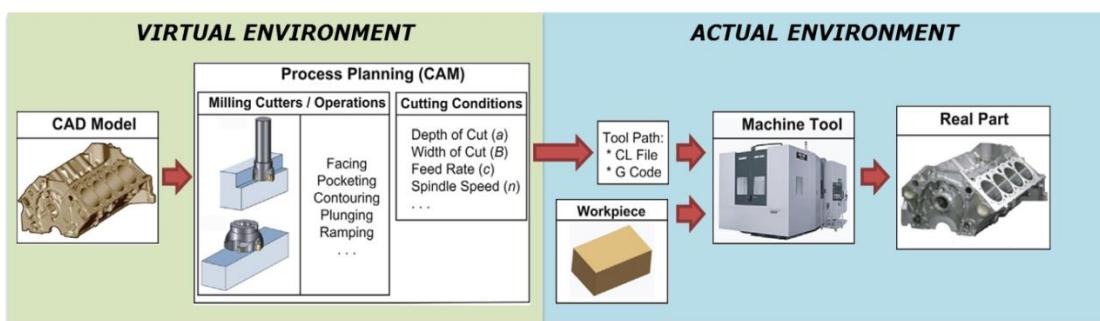


Figure 2.1 Virtual and actual manufacturing concept

Source: Altintas *et al.*, (2014)

Generally, there are 2 categories of machining simulation approach; Geometrical simulation and Physical simulation, as shown in Figure 2.2. Geometrical simulation approach is a method to verify the reliability of NC program graphically in

terms of collision interferes, finished parts model and machining time prediction. It also provides geometric information for physical simulation (Bouhadja & Bey, 2014). On the other hand, physical simulation approach is the method to predict machining process parameter such as surface roughness, cutting forces and tool wear (Y. Zhang et al., 2011). The output of physical simulation is influenced by geometrical simulation information and the selection of cutting tool material. This research focuses on development of geometrical simulation and optimization in CNC machining simulation for milling processes. The research presents the contributions of development and implementation of programming codes (Visual Basic 10) in CAM system interfaces (NX-CAM 10).

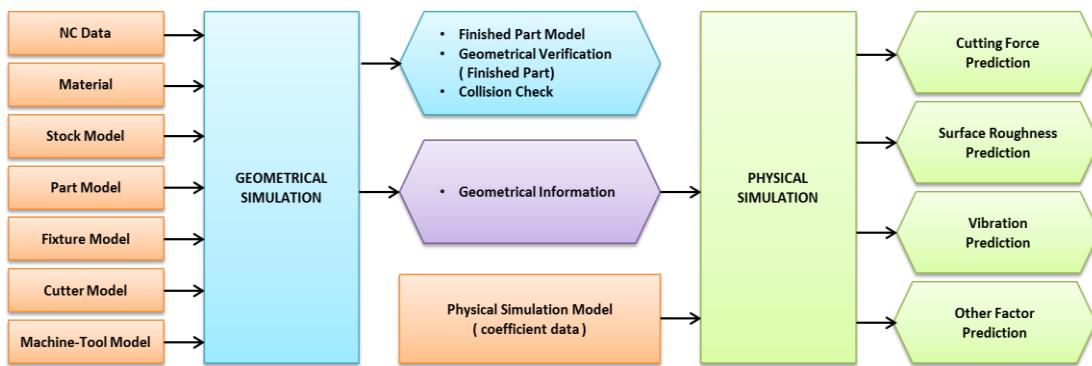


Figure 2.2 Machining simulation method

Source: Bouhadja *et al.*(2014)

Milling machining is a process where the material removed from the workpieces by using rotary cutter with the direction following the tools axis. The capability of milling processes to produce machined products with high precision and accurate size has made milling widely used in the industry. There are two basic of milling configurations, which is vertical mill and horizontal mill. Each configuration divided into two types which is turret mill (stationary spindle) and bed mill (movement spindle) (Hou, 2015). Typically, CNC milling machine made with basic of 3-axis cutting configuration. For example vertical bed mill type, where the working table provide X-Y axis movement and spindle provide Z-axis vertical movement (Figure 2.3). However, there is a limitation for 3-axis machining, where incapable to perform machining for complex geometry parts or undercut machining within single operation. Thus, there is another solution by adding 4 axis to rotate the workpieces in order to provide one cycle machining for complex geometry parts within single operation, called computer numerical control rapid prototyping (CNC-RP) (Frank, 2004). The setup of CNC-RP

approaches shown in Figure 2.4, where workpieces mounted between two opposite chucks and rotary indexer will rotate the workpieces along axis of rotation. This approaches allow the workpieces to be rotated within its axis without re-clamping the parts. In this research study, the main focus is on 4-axis milling machining simulation, which is the integration of 3-axis CNC vertical bed milling machining with additional 1-axis rotary indexing devices.



Figure 2.3 Makino KE 55 CNC 3 axis milling machine

Source: <https://www.bidspotter.com>

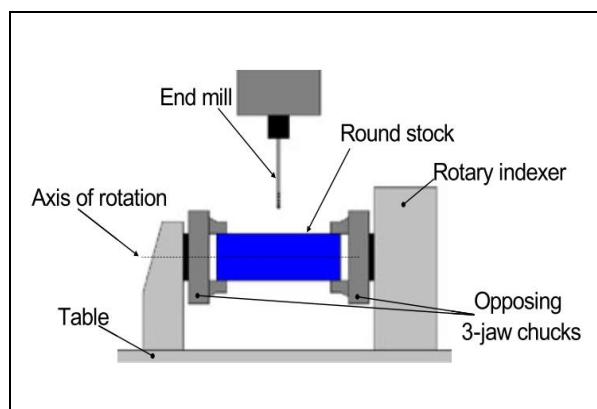


Figure 2.4 CNC-RP methodology set-up

Source: Frank (2004)

Machining process planning is one the crucial tasks and highly depend on the machinist experience (Xu, Wang, & Newman, 2011)(Relvas & Simoes, 2004). When dealing with new machining conditions, the trial and error approach is a common method adopted. A demand to increase productivity is the main challenge in global manufacturing and each of companies will compete to reach the targets. Therefore the trial and error approach seamlessly applicable, but it will cause a major impact on productivity in terms of machining time and costing (El-Mounayri, Kishawy, & Tandon, 2002). There are few ways to improve the current approaches. For example, the generation of numerical control (NC) codes from machining processes. In conventional approach, to develop NC codes needs great theoretical depth and practicality in order to ensure the feasibility of developed code to execute actual machining (Yongxiang Li, Lu, Yu, Guo, & Zhang, 2017). There are few other methods that can be employed by the integration of advanced tool and programming coding. Lack of technical knowledge and integration capability of CAM system with hardware is one of the reason why most companies suffered in the production stage. Particularly in milling processes, there are several gaps that need to be resolved in order to optimize the machining simulation to the required level of generality, reliability and accuracy.

Figure 2.5 illustrates the gap overview between standard CAM operation and optimized operation (El-Mounayri et al., 2002). Therefore, the investigation of machining simulation routines in CAD/CAM system by using programming code are expected to bridge the gap and optimize the machining routines processes. In addition, the development of automated machining simulation model and reliable prediction system is crucial to manage the other processes. In that way, the machining industries are able to achieve the target for higher productivity and excellent parts accuracy at lower cost. Further development of machining simulation technique is necessary to enhance the machining capability and process efficiency. This chapter is dedicated to present an overview on state of the art of CNC machining simulation routines. The structure of the literature reviews outlined in this chapter is shown in Figure 2.6. A review is beginning with CNC machining processes overview. The next part of the chapter is to review a process planning fundamentals in CNC machining. After this, the methods of simulation routines in CNC machining are described. Finally, the significance and application of programming in CAD/CAM systems is elaborated.

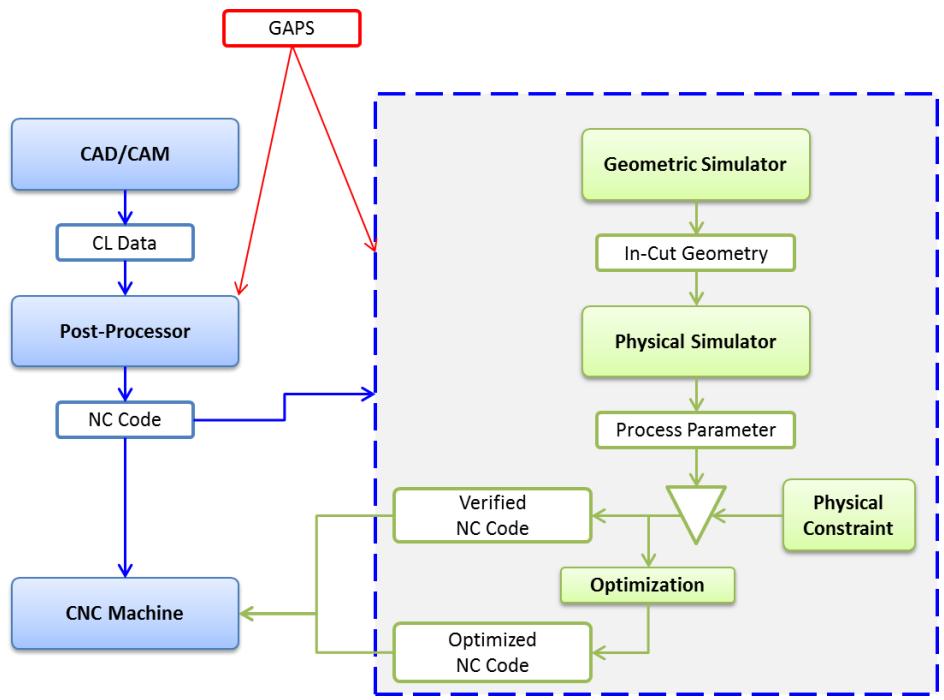


Figure 2.5 Gaps between CAD/CAM automated and optimized CNC machining

Source: El-Mounayri *et al.* (2002)

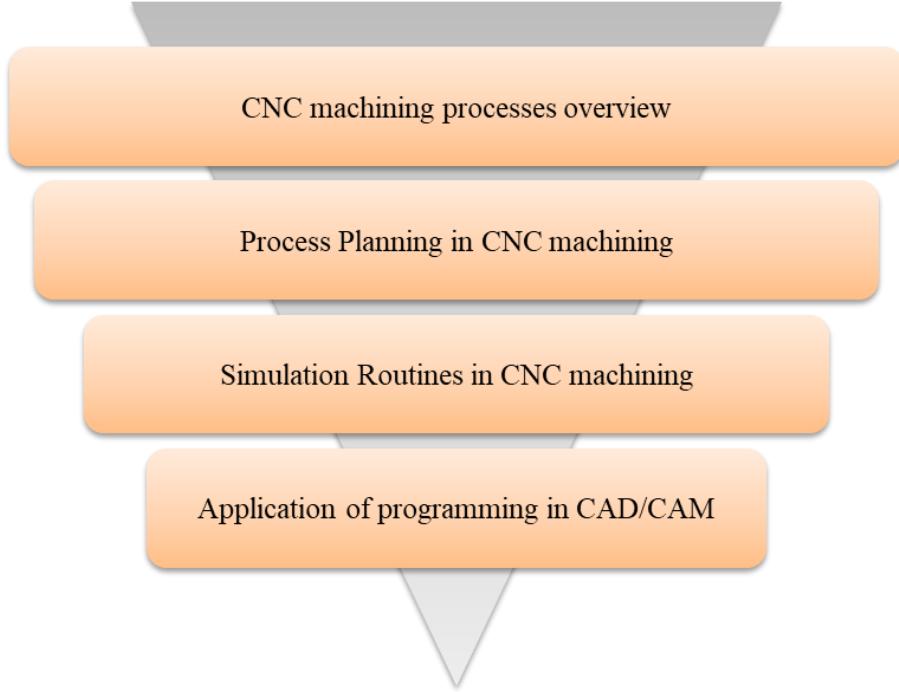


Figure 2.6 Literature review structure

2.2 CNC Machining Technology and Processes

2.2.1 General Terminology

Computer numerical control (CNC) has brought new technology phase in metal-machining sectors. The integration of CNC technology and machine tools provide an opportunity for machining industry to produce quality parts in terms of geometry and accuracy (Krar et al., 2005). This technology is capable to produce the same product geometry repeatedly in a batch, with proper controlled parameter and machining setup. The CNC instruction allows the machine tools to operate automatically based on the parameters that have been set initially. CNC technology is categorized under soft automation group, known as flexible or programmable automation (Kalpakjian and Schmid, 2006). The flexibility is justified through the utilization of machine computer control, which able to produce parts with a complex geometry. Therefore, CNC systems can be considered as an efficient and profitable technology. The application of CNC in machining also managed to reduce time consumption which is important aspect in manufacturing sector at the same time increase productivity and process flexibility (Gjelaj, 2010).

The common development of CNC machine is to generate tool motion path and machining operation with particular machine tools. It is a specialized automation application and operated through a discrete numerical value (Sharma, 2007). The CNC machine fundamentals routines can be defined as predetermined sequence of machining operation at the predetermined necessary speed to produce a part with the right shape geometry and provide completely predictable results. The CNC machine is capable to be re-programmed, therefore a different part can be reproduced according to required quantity (Kalpakjian and Schmid, 2006). An Electronic Industry Association (EIA) defined a CNC technology as “A system in which actions are controlled by the direct insertion of numerical data at some point. The system must automatically interpret at least some portion of this data” (Sharma, 2007). This means, the function of CNC system is to receive the input data or instruction in numerical form, then the system will interpret the data and simulate cutting tools accordingly as shown in Figure 2.7.

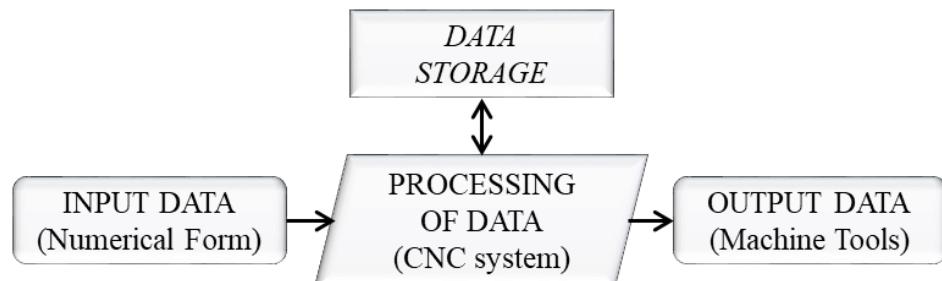


Figure 2.7 Functional element in CNC

Source: Krar et al. (2005)

2.2.2 NC parts programming

In general, NC parts programming is purposely used to develop NC codes which is used to provide the instruction to the CNC machines. A series of instructions code is necessary as the input. CNC programming is considered as process planning tasks used to machine the part which initially comes from the drawing. Basically, the sequence of part programming are as follow (Suh, Kang, Chung, & Stroud, 2008):

-
- 1. Analyse the part drawing.
 - 2. Decide on the removal volume and select the machine.
 - 3. Decide the jig and chuck.
 - 4. Decide on the setup, machining sequences, cutting starts points, cutting depth for roughing and finishing allowance.
 - 5. Select tools and tools holder and to decide the tool position.
 - 6. Decide on the technology data such as cutting parameter and coolant on or off.
 - 7. Generate the part program (including post-processing).
 - 8. Verify the part program.
 - 9. Machine the parts.

The operations from stage 1 until stage 6 are categorized under the preparation stage, where the part drawing and the machining strategy is analysed to develop the machining program. These operations are also called as “Process Planning”. Process planning is executed by machine operator which required high level of knowledge regarding to CNC equipment, machine tools and machining theory in order to obtain optimal machining process. Unfortunately, it is difficult and not practical to always rely on the expertise. Hence, a study on Computer-Aided Process Planning (CAPP) is necessary in order to adopt the automation element in machining process planning. Computer aided process planning (CAPP) is a method to automatically develop the process plan from the geometrical model of the component and build a process plan by implement algorithm design, machining code file and decision logic (Priti, 2016). Furthermore, the operations from stage 7 onwards are purposely to control the CNC machine. These operations can be executed in two ways, which are manual and automatic programming. In manual programming, the machine operator directly edit the parts program in CNC-readable code instructions (EIA/ISO), such as G-code or M-code. Generally, G-codes are performed by the CNC processor and control the machine

movement such as rapid transverse, linear interpolation, circular interpolation and cutter compensation (Krar et al., 2005). M-codes are machine codes, used to operate most of the basic electrical control functions such as spindle switch, coolant, spindle rotation and tool change (Krar et al., 2005). Meanwhile in automatic programming, the machine operator edit the programs through computer, in terms of graphical or instruction language (Suh et al., 2008). Then, the instruction language is converted to machine-readable instruction to execute the machining processes.

2.3 Process Planning in CNC Machining

2.3.1 Process Planning Overview

In manufacturing industry, process planning need to be carried out thoroughly to ensure the parts fulfil the geometry requirements and design specification (Scallan, 2002). Process planning is concerned with the selection method to produce the parts in terms of tooling, fixtures, machinery, operation sequences and assembly. Traditionally, this entire process is executed by the process planner and documented in routing sheet. All of these factors contribute to highly labour-intensive, time consuming and heavily rely on the process planner experiences (Kalpakjian & Schmid, 2006b). Process planning can be defined as an engineering activity to determine an appropriate procedure for transforming raw materials into a final parts based on the engineering design (Scallan, 2003). A process planner must be efficient and complete the task according to the schedule. Therefore, it is important to ensure that the parts is machined in correct specification, high geometry accuracy, at possible minimum cost and completed on time. The nature of CNC machining involves a lot of variables, data and information which lead to the complexity of the process planning tasks. All data and information required should be evaluated carefully to meet the requirements of the plan. Therefore, the use of various aid-supports is needed in order to obtain an optimal machining process, such as CAD/CAM and CAPP. Generally, there are two approach employed in process planning which are manual process planning (MPP) and computer-aided process planning (CAPP). Figure 2.8 shows classification approach to represent a process planning.

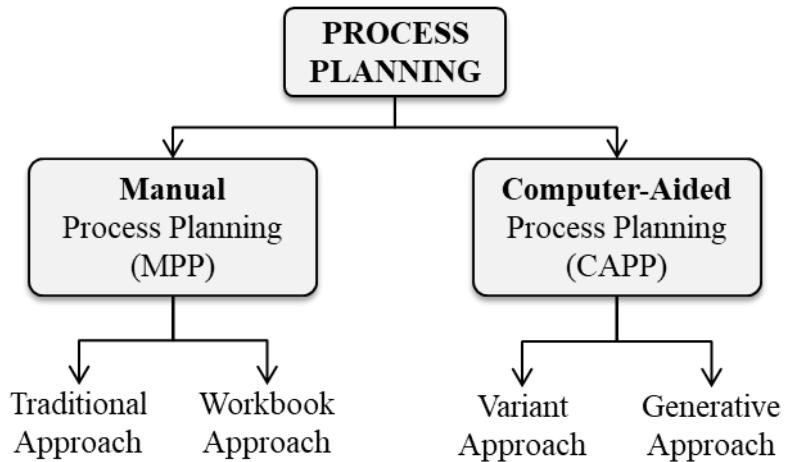


Figure 2.8 Classification of process planning

Source: Scallan (2002)

2.3.2 Manual Process Planning (MPP)

Manual process planning (MPP) is totally based on machining planner's experiences, skills and knowledge in terms of machining equipment, processes and tooling. In traditional approach, process planning is performed manually by experienced process planner with manufacturing background to decide on the type of material and processes to be used. The tools, feeds and speeds recommended for the particular processes are referred to manuals work sheet. All the particular procedure and operation are documented in the process planning template, called as Routing Sheet (Scallan, 2002). In some companies, process plan are manually classified and stored in workbooks (Golam & Deloyer, 2010). Workbook approach is a derivative from the traditional approach. A sequence of operation for the manufacture certain types of parts is loaded into the workbook. When the required process has been identified, the operation sequences will be selected in workbook and incorporated into the process plan (Scallan, 2002). The need of shorter processing time and chasing the customer demands has leads the industry to initiate the automation in production cycles.

2.3.3 Computer-Aided Process Planning (CAPP)

Computer-Aided Process Planning (CAPP) is the system where computers are used to assist or replace human intervention in order to produce a better process plans in optimum time (Anderberg, 2009). The fundamental concept of CAPP is to automate the

process planning, which aims to reduce time and efforts and providing high process plan consistency. The variant process planning approach, also called as retrieval approach, can be described as an advanced manual approach where the standard plan retrieve by the computer and modified to suit a given parts (Golam & Deloyer, 2010). The plan is displayed for reviewed and printed as a routing sheet. It includes the information such as types of machines and tools, the sequences of manufacturing operations to be performed ,speed, feed and estimated time consumed for each sequences (Kalpakjian and Schmid, 2006). The generative process planning approach is the nearly an automated approach. The plan are developed by the computer in terms of decision logic, formulae, algorithm and geometric analysis (Scallan, 2002). However, the generative process planning approach is complicated because it contains detailed information of the parts geometry and dimension. This approach is capable to develop a new plan instead of using and modify existing plan, as performed by the variant approach (Kalpakjian and Schmid, 2006). Basically, in product design and manufacturing, process planning plays an important role to improve productivity and minimize production time (Bahaley & Maldhure, 2015). The implementation of CAPP has been study by generating NC codes in CAM software (Turley et al., 2014). The algorithm is developed to generate tool path and integrated with commercial CAM software. The basic comparison between manual process planning (MPP) and computer-aided process planning (CAPP) is shown in Table 2.1.

Table 2.1 Comparison between MPP and CAPP

Manual Process Planning (MPP)	Computer-Aided Process Planning (CAPP)
Time consuming	Shorter Time
Require skilful technician	Automated
High tendency to human error	Capable to anticipate human error

Source: Joshi et al. (2015)

2.4 Applications of Programming in CAD/CAM System

2.4.1 CAD/CAM system overview

Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) is the technology that has been widely used nowadays. Computer-Aided Design (CAD) can be defined as a computer-based tool for creating 2D wireframes and 3D graphics objects (Lutters, 2014). CAD has been used in many ways in the industry and usually works to produce engineering drawings. Subsequently, Computer-Aided Manufacturing (CAM) can be defined as a computer-based systems that used to plan, manage and control the operations of manufacturing plant through computer interfaces with the plant's production resources (Makris, Mourtzis, & Chryssolouris, 2014). Generally, the CAM system serves as an intermediary between CAD and NC machines. Any drawing and design that created by CAD system required a translation tool in order to generate NC for CNC machine. Therefore, CAM systems will act as a translator tool for the coding generation purposes (Dimitris Mourtzis, Makris, & Chryssolouris, 2014). The illustration of data interfaces between CAD, CAM and CNC has been shown in Figure 2.9. CAD/CAM system is consisting of two computerization method in programming. CAD is computer-supported of design that capable to draw three dimensional model of the product. CAM is computer-supported of machining that capable to simulate machining cycle. The integration of CAD and CAM systems allows the user to generate CNC codes directly from the designed components (Jambor & Majerik, 2009) (Majerik, Bajcik, & Jambor, 2010). The CAD/CAM systems has rapidly developed and become powerful modelling technique especially for complex surface geometries. The implementation of CAD/CAM system in production and manufacturing industry have inspired significant enhancements in machining operation, especially in milling and turning operation where it leads to the reduction of machining time and optimized finishing operation. (Ramos, Relvas, & Simões, 2003) (Chakravarti & Yadav, 2019).

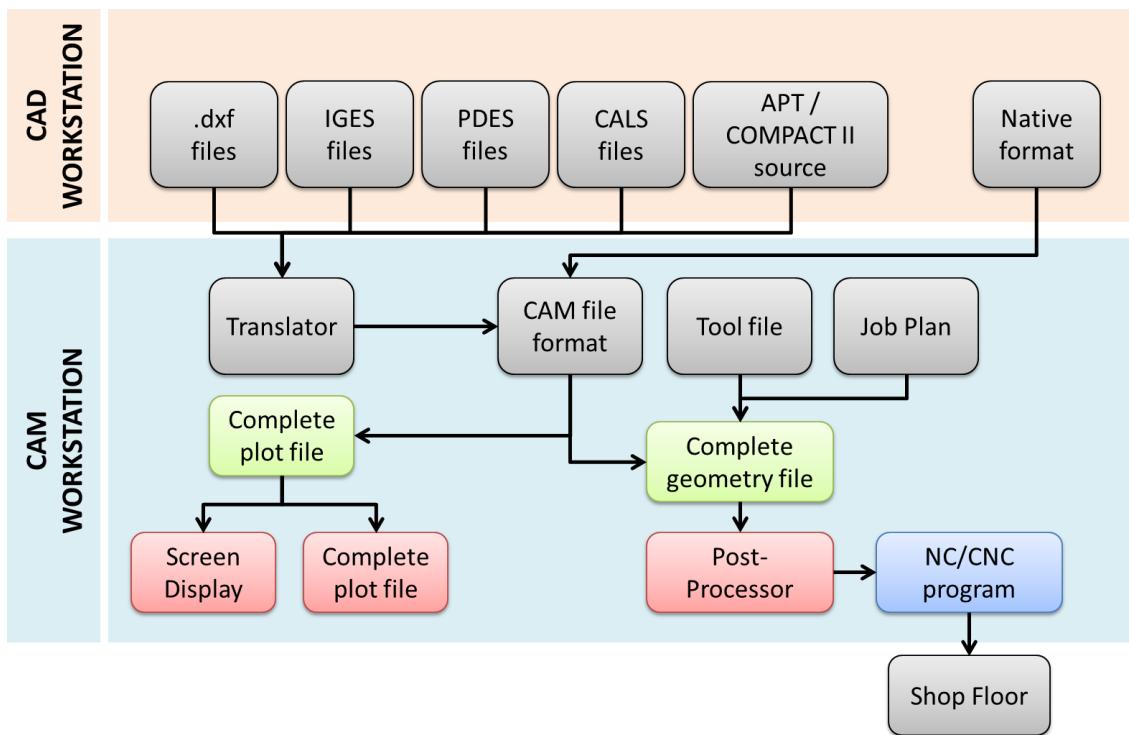


Figure 2.9 Data interfaces between CAD, CAM and CNC

Source: Rehg & Kraebber (2005)

2.4.2 Classification of CAD/CAM software

Nowadays, there are various kind of CAM software available in the market. The main function of CAM software is to assist the milling and turning operation sequences by focusing on narrow tasks. The software provides adequate capability in geometrical modelling. However, some of them are integrated with existing CAD system. Generally, CAM software can be classified into three categories based on the integration to the CAD system as shown in Table 2.2. Pro/ENGINEER, CATIA and NX is a major CAD system that already built-in with a CAM module. Solidworks and Autodesk Inventor provide CAM modules from third-party software which is nearly the same as the major CAD system as well. All such CAM modules offer an excellent capabilities in virtual machining to support comprehensive scope related to machining sequences, including profile milling, volume milling, surface milling, hole-making, and text-engraving (Chang, 2015). Development of CAM module fundamentally started with CAD and then is expanded into CAM either through its own acquisition or via third party. On the other hand, the development of stand-alone software such as MasterCAM, SurfCAM and GibbsCAM are intentionally to support virtual machining,

which is essentially CAM-centered. In some circumstances, these tools provide excellent performances in terms of generating a toolpath for contour surface milling including the constant scallop height where this function are unavailable in Pro/MFG.

Table 2.2 CAM software classification

CAM AS MODULE	CAM AS THIRD-PARTY SOFTWARE	CAM AS STAND- ALONE
Pro/MFG,	CAMWorks (www.camworks.com)	MasterCAM
Pro/ENGINEER	* <i>Integrated with SolidWorks</i>	(www.mastercam.com)
CATIA,	InventorCAM	SurfCAM
CAD/CAM/CAE	(www.inventorcams.com) * <i>Integrated with AutoDesk Inventor</i>	(www.surfware.com)
NX Unigraphics		GibbsCAM (www.gibbscam.com)

Source: Chang (2015)

2.4.3 Adaptability of programming code in CAD/CAM system

Shao Wei (2014) has developed a digital management program called "unified digitization system" for the part parameters based on UG (Unigraphic NX) platform (Wei, Chong, Jing, Ying, & Junjie, 2014). This program is developed to overcome inconsistent issue in digital data management system in terms of product design, manufacturing information and detection of digital plant construction. Nowadays, modern industries require a digital management platform that capable to store uniform data related to product design, process design and manufacturing processes. Therefore, this system is developed to provide solutions by combining all digital information in a single database. Structured Query Language (SQL) server database was established for database management in order to centralize all the parts parameters information. Figure 2.10 illustrates the structure of digital management system and inspection planning. Databases management consists of 3 major components which are product design, information collection and inspection planning. NX software and C# is the main development platform used to create product design, also to build an application for inspection planning and information collection algorithm.

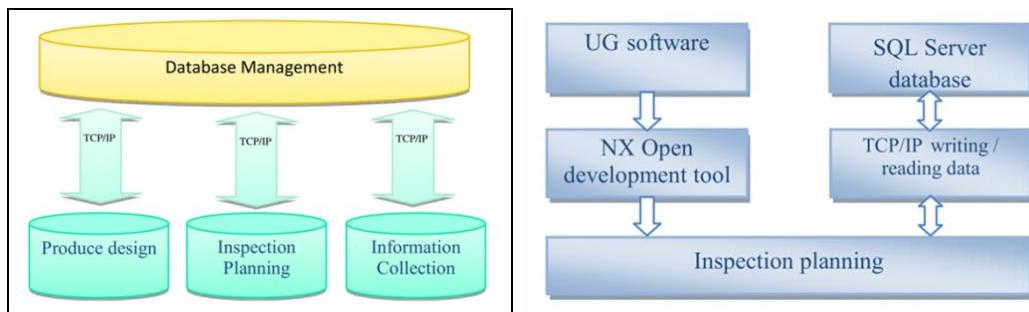


Figure 2.10 Structure of digital management system and inspection planning

Source: Wei et al. (2014)

Palekar (2014) has developed a Master Model application to improvise the updating process for assembly models (Palekar & Khairnar, 2014). The application was developed to address the problems associated with the parts assembly in NX CAM systems. In modern CAD/CAM system, updating information for assembly part with hundreds of sub-assemblies component is considered as critical task. A slight mistake while updating the parts information (parameter, dimension and etc.) can lead to error in the overall assembly model. Additionally, it will indirectly affect the time consumed and requires high graphic and high probability to cause system memory error (out of memory, memory access violation and etc.). The Application Programming Interfaces (API) has been used to develop the proposed application within Microsoft Visual Studio. For programming purpose, the combination of Journaling Tools and VB.net has been employed. The user will enter the necessary input into the developed application, and then the input will be transferred to NX through excel files. The application will run the updating process on the NX assembly model in background mode. After that, the application will generate an error report, if the error presents during the assembly updating processes (Figure 2.11). Through the report, the part that cause the error can be identified and corrected individually later. Master Model application manage to reduce the product life cycle time and percentage of error generated during NX parts assembly information updating processes.

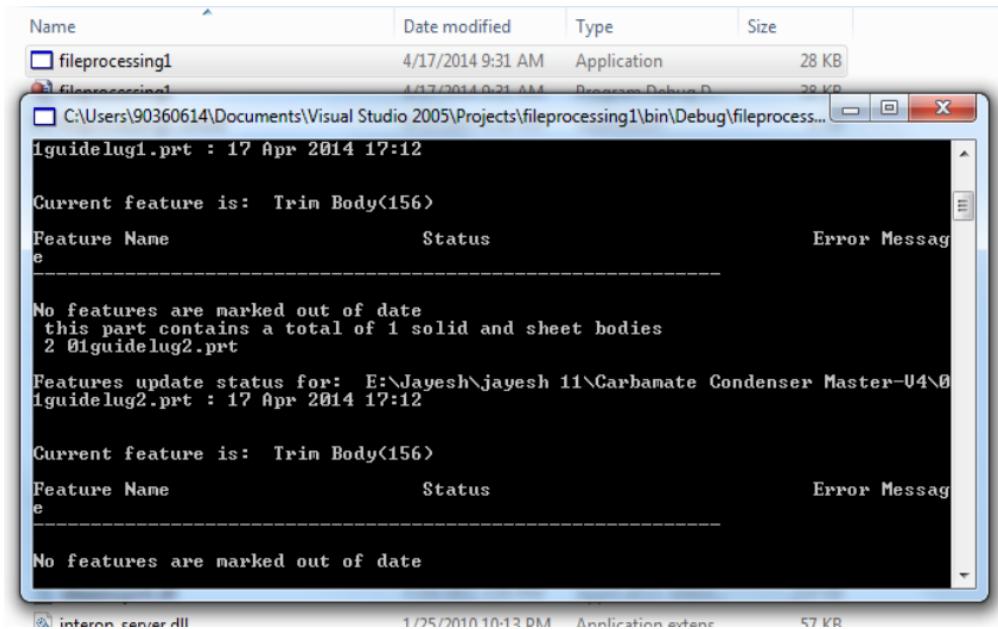


Figure 2.11 Error generation report

Source: Palekar & Khairnar (2014)

Nowadays, design and modelling of products are aided through CAD/CAM systems. Each of design processes possessed natural routines tasks that possibly to be automated. Zbiciak (2015) worked out an application to automate the engineering task in NX CAM environment that used to generate 3D design for gear wheel model called, The Generator Module (Figure 2.12). The main function of this module is to develop and modelling the spur and helical gears. There have two types of validation test, the first test is to validate the design parameter calculation and second test used to verify the geometry involutes between proposed and standard approach. The program was developed using NX modelling function by manipulating the vector graphics to generate a journaling code for customization. According to the simulation results, the generator module manages to facilitates the constructional process design within minimum time and process planning. The main advantage of the application is the ability to minimize the modelling time compared to conventional methods (Zbiciak, Grabowik, & Janik, 2015).

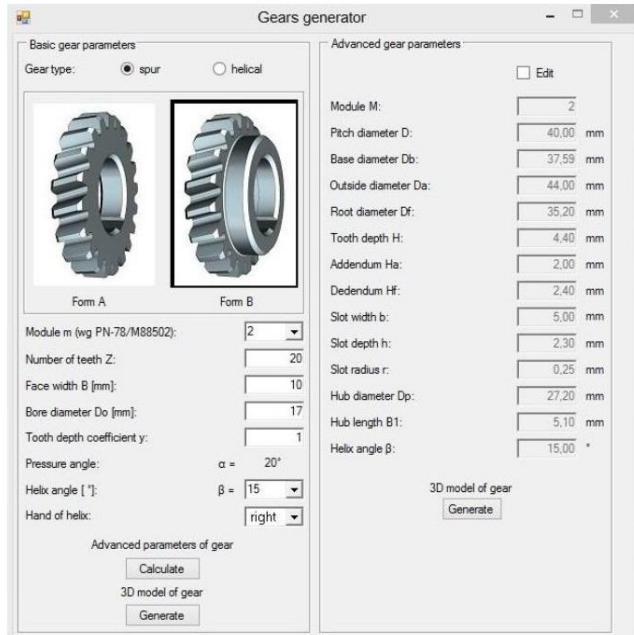


Figure 2.12 The generator module GUI

Source: Zbiciak et al. (2015)

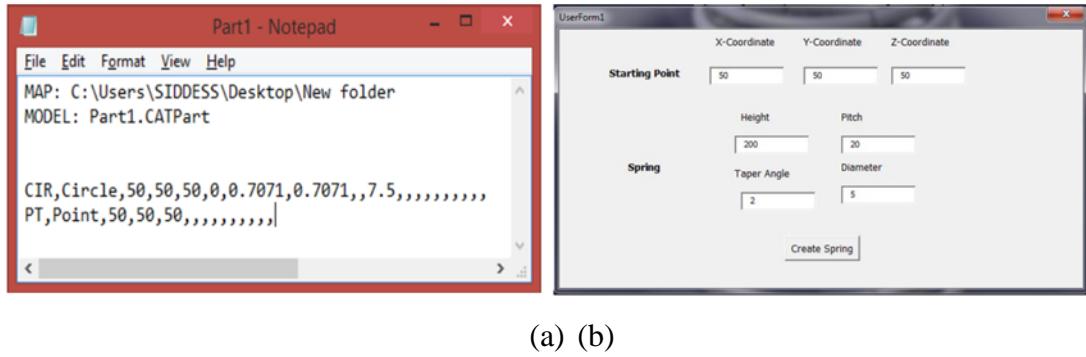
Gawai (2015) develop a customized software to design a solid shaft coupling assembly model by using Unigraphic (NX) and Knowledge-Fusion (KF) Programming (Gawai, 2015). Knowledge-Fusion (KF) is an integrated tools that permits the NX end user to extend the NX capabilities by increasing the design speed and intelligently control the own functions as needed by the developer (Siemens, 2018). KF supports all the NX functions that are used to automate the required processes. An Open User Interfaces styler was utilized to develop and create a dialog box for NX user interfaces as shown in Figure 2.13. The customized software used to automate the design process for shaft coupling modelling, where it managed to decrease the processing time and effectively simplify the modelling process planning.



Figure 2.13 User interface of coupling assembly

Source: Gawai (2015)

In CAD modelling, the modification processes require a repetitive procedure to finally meet the desired model. Instead of repeating procedure, there is another way to automate the routine by constraining several parameters. Siddesh (2015) has introduced an automation method to generate the CAD models in CATIA systems by using programming application (Siddesh & Suresh, 2015). In general, automatic generation of CAD modelling can be executed in two methods as shown in Figure 2.14. First method, the coding was written manually then uploads to the program while second method is utilizing macro tool that available in CAD/CAM system. Manual program used a user form interface that has been developed in visual basic application (VBA). It has only two buttons, save and open. The save button is used to store the parameters, while the open button is used to edit the parameters. However, manual method is more vulnerable to errors due to the coding was written manually before uploading into the application. This method is also complicated and takes a long time for repeating processes. Therefore, the author develops a program to implement the automation process for CAD generation. Standard user form was used as an interface in macro method and able to help user to interact with CAD model. It contains a labelled text box and also a commands button to start the design process. The user just needs to enter the value into the box and then press "create spring" button. Using the proposed method, the time required to generate the CAD model for repetitive work can be reduced up to 90%. In addition, the proposed method also improves the consistency of the design model and reduces the probability of human error.

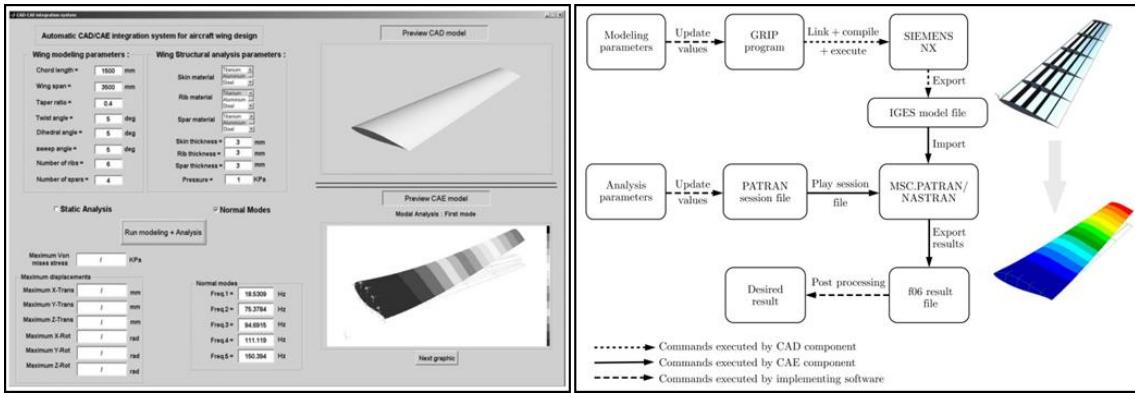


(a) (b)

Figure 2.14 a) Manual generation program b) Auto generation program

Source: Siddesh & Suresh (2015)

Benaouali (2017) developed a procedures to automate the integration between Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE), which then being used to make design and analysis on aircraft wings (Benaouali & Kachel, 2017). The proposed procedures are developed with the use of Graphic Interactive Programming (GRIP) tool automation that available in the Siemens NX software. The main purpose of the integration is to eliminate the repetitive cost effort and to simplify the optimization procedure. During the aircraft model optimization phase, there is a several data changing in design, geometric and analysis parameters. The model needs to be updated each time the parameters changed. This task will be complicated and time consuming if performed manually, particularly in the case of model that have large number of parameters. Therefore, it is important to integrate CAD and CAE as well as automate the procedure in order to avoid designer's intervention at each iteration. Figure 2.15 (a) shows the developed integration procedure between CAD and CAE. The GRIP program was employed to handle the modelling parameters data and send the compiled information to Siemens NX software. For the analysis of parameters, PATRAN software was used to send the information to NASTRAN software. PATRAN and NASTRAN is the post-processing software that use for Finite Element Analysis (FEA), which provide meshing and analysis setup for solid modelling. Once all the setup procedures and analysis completed, the result file in f06 format is produced and will be extracted by necessary application to generate the desired results. Figure 2.15 (b) is a graphical user interface developed using MATLAB to facilitate the integration system.



(a) (b)

Figure 2.15 a) CAD and CAE integration procedure b) Application GUI

Source: Benaouali & Kachel (2017)

Nafis (2017) has developed a machining simulation programs to improvise the manufacturing process planning for CNC Rapid Manufacturing (CNC-RM) applications (Nafis et al., 2017). This simulation tool is intended to enhance the automation level in machining process planning. In principle, planning task in the machining operation is correlated with machinist experienced, skill and time. A few improvements in CAM technology was established to assist the user who have minimum skill to build machining operation. A customized program has been developed using visual basic programming and incorporated into NX platform. It equipped with simple Graphical User Interfaces (GUI) that has a few inputs to be defined by the user. To validate the stability, the program was used to simulate several models that have different features in terms of geometry and size. The simulation results have shown that the developed program manages to build a complete machining operation and successfully minimizes the time spent for process planning up to 79% compared to conventional approach.

2.4.4 Selection of CAD/CAM software

The selection of CAM platform to simulate and verify the machining operation is very important. Every single of CAM software owned advantages and disadvantages. Therefore, the key element of selected CAM system must be identified and tally with the intended requirements and analysis. In order to perform various simulation tasks in 4 axis machining operations, the CAM system must possess an ability to be customized and integrated with the mainstream programming languages such as Visual Basic or C++. Therefore, based on aforementioned literature, NX CAM (Unigraphics) is the

most suitable software to cater simulation routines and process planning in 4 axis machining. NX CAM provides the ability to expand the common simulation approach through NX Open secondary development include Common API (Application Programming Interfaces), Journaling, Classic APIs, Knowledge Driven Automation and other NX Toolkits (Wei et al., 2014) (Pechenin, Rusanov, & Bolotov, 2018). APIs in NX Open allows the user to develop applications for extending NX function through open architecture based on high level programming languages, such as Visual Basic, C#, JAVA, Python and C++ (Zbiciak et al., 2015). Figure 2.16 shows the available journal language translation in the NX CAM systems, version 10.

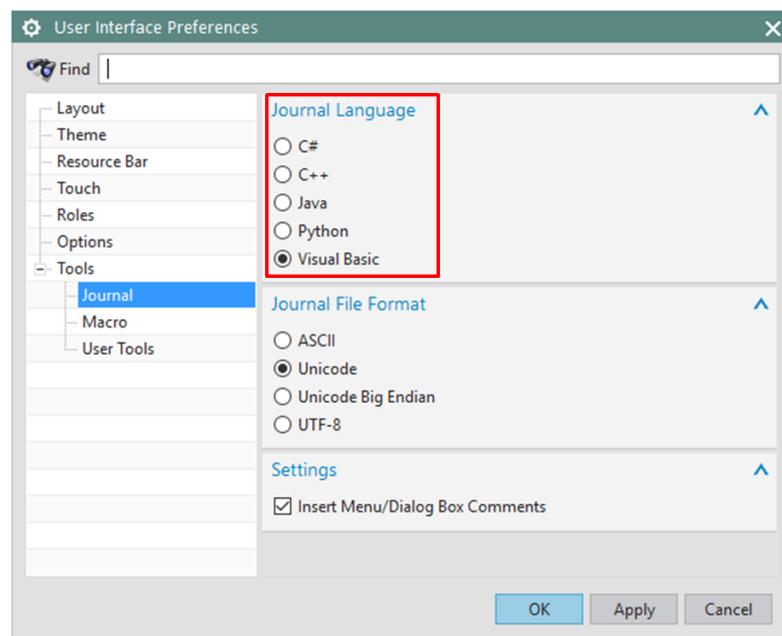


Figure 2.16 Journal language available in NX CAM version 10 system

2.4.5 NX CAM software

NX CAM software is the digital product that has been developed by SIEMENS PLM in order to provide a complete proven system for machine tool programming (Siemens, 2007). This software has the capability to reduce programming time through automation features that have been built-in inside the systems. NX CAM software provides a multi-functional programming that allows user to address many tasks in one system. NX is leading parametric modelling CAD software, where it offers various tools of automation, such as Knowledge Fusion, GRIP programming, Macros, NX Open, Journals and User Defined Objects (Benaouali & Kachel, 2017). The flexibility

of NX CAM can be view from the incorporation of CAM simulation with others programming codes via NX open API (Application Programming Interface) function. An API can be described as a "backdoor" to NX and become a platform to develop a customs features. NX open API allows the user to manipulate the programs and customize the NX functions (Siemens, 2014). The key advantage of this feature is it can accelerate repetitive tasks by the developing a customized program or application. Manipulating programming in NX CAM can be coded through a NX open API wizard in Visual Basic Studio (Moi, 2013). Simple NX Application Programming Interfaces (SNAP) is one of the API functions that is use to further extend the NX capability in programing customization (Stănescu, Blaga, & Budoş, 2019). The benefit is that small applications created this way can often speed up repetitive tasks and capture important design process knowledge (Siemens, 2014).

2.5 Simulation Routines in CNC Machining

2.5.1 Definition of Simulation

Simulation in manufacturing is defined as the imitation routines of the selected operation in real processes for pre-evaluate purposes. The behaviour of machining processes and response parameter is studied by developing a simulation model for cutting operation before proceed into real machining. The simulation is carried out to identify the issue or problem in early stage of machining (Anderberg, 2009). It is important to investigate the machining processes by simulating the operation to ensure the result of the processes is similar to the design parts. Simulation can be carried out in CAM software or direct on the machine control panel. Besides that, simulation analysis also permits the user to identify the effect of changes and can act as a design tool to develop a new system (Banks, Carson, Nelson, & Nicol, 2010). Other than that, it is also can be used as a tool to analyse different machining scenarios, not only rapidly but also without any risk, damage and waste of workpiece. In a broader context, simulations can be defined as a set of tools, methods and technology platforms for experimentation and validation. It provides space for researchers to perform a study related to product, process or system design (D Mountzis, Doukas, & Bernidaki, 2014). Developing new algorithms framework to control the machining simulation is a challenging task and

requires high level of skills. The improvement of simulation process planning and procedures has widened the application of programming language in CAM software. In addition, the application of indexer in milling machine has permitted workpieces to be machined from various angles. This is an advantage for rapid manufacturing processes where the material can be removed from different orientations in one setup until the part visible. On the process planning perspective, this approach will require extensive utilization of CAM systems to perform various simulation routines and generating complete machining program. Recently, advanced tool in CAM system allows the code translation process where the user can record and translates the commands they used into programming language script. Thus, it establishes the relation between the instructions and programming code which broaden the way for customization and integration with different API (Moi, 2013). Besides, several decision making tools can be embedded in the algorithms to control the simulations process and generate desired results.

2.5.2 Simulation Routines in CNC Milling

For the past several decades, CNC milling methods have significantly influence a revolution in manufacturing processes. It commonly used in industry for machining parts to obtain a precise size and geometry of the product. End milling is the most essential process because of its capability to remove materials at faster rate with a reasonable good surface finish (Patel, 2015) . The machining simulation is purposely for reducing process time and material wastage, due to try-and-error approaches. Machining error such as tool path error and cutting error can be detected and predicted during simulation (J. Zhang, Ong, & Nee, 2006). CNC milling machining simulation is economic and conducive for verification purposes. In recent advancement of technology, the adaptation of computer numerically controlled (CNC) in advances machine tools has been established to automate the milling processes. However, the capability of CNC milling is not only focuses on automation, but also need to consider the methods for process simulation (Patel, 2015) (Zhao, Cao, Xiao, Liu, & Jun, 2020). In 4 axis machining simulation, there are a few factors that affect response parameters, which are cutting orientation and cutting parameter. These two factors are directly influence overall machining time and surface quality (Nafis, 2014) (Mikó et al. 2017).

2.5.3 Cutting Orientation in 4 axis Milling Simulation

The complexity of the parts to be machined is directly related to the milling operation that needs to be chosen for the machining process (Joshi & Mukund, 2015). Typically, it is determined based on material properties, surface finish and features from multiple orientations. Depending on the parts geometry and complexity, the increasing number of cutting angle is necessary to guarantee that the parts are machined completely. Generally, 4 axis indexer devices are used and act as a clamping device that permits the parts to be rotated in one rotation axis, as shown in Figure 2.17. The raw material of the workpieces can be removed by the cutting tool in various orientations until the desired part is obtained. Series of research work was carried out to detail up the machining simulation based on multiple orientation.

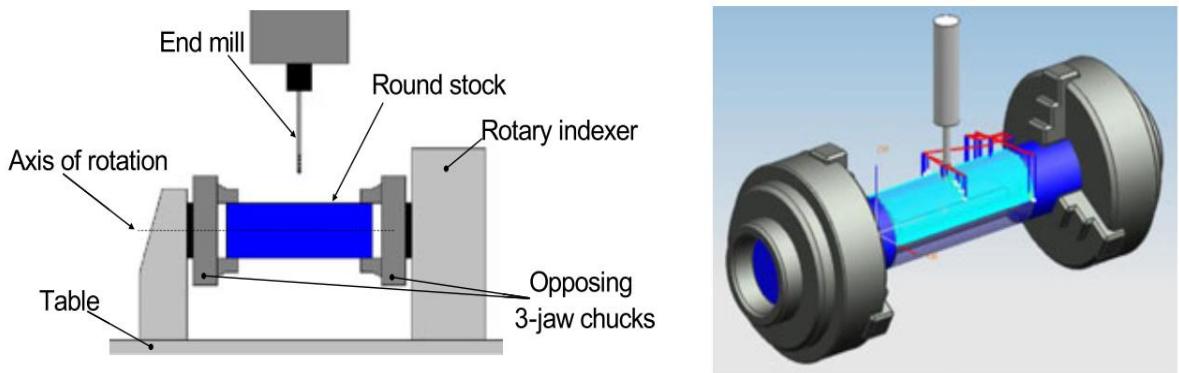


Figure 2.17 4 axis indexer setup

Source: Nafis (2014)

Frank (2004) has established a “feature-free” method for CNC milling process planning and proposed a new approach to machine variety of parts with minimum human intervention (Frank, 2004). A 3-axis milling with a fourth axis rotation indexer was employed as an effective way to perform rapid machining (RM) processes. The proposed method was capable to execute the machining processes continuously without re-adjustment in between the operation. It involves milling parts by using a plurality of 2.5D tool path oriented about one axis of rotation. A round stock material with specific diameter was mounted and rotating between the opposing chucks. In general, process

planning in rapid machining was classified into three categories consist of tool path planning, fixture planning and tool selection. In tool path planning, a simple layer-based method was employed to machine the parts according to respective cutting orientation. Simple layer-based method was originally applied in traditional rapid prototyping processes. However, rapid prototyping employed an additive process while rapid machining that use in this approach is a subtractive process. The goal of the proposed method is to ensure that all specified surfaces of the workpieces were fully machined when all defined orientations are completely rotated. Figure 2.18 has shown the processing step of the proposed approach. The number of orientation and tool geometry can be derived from CAD slice data. In fixture planning, the method to mount the workpieces is slightly different with common milling machining. The fixturing approach in rapid machining employed “sacrificial-support” concepts. This fixturing method allows the workpieces to be rotated without need to reset the machining references points. The sacrificial supports must be added to the ends of CAD files model. The diameter size and length of sacrificial supports was calculated depending on the parts size and geometry. There have two types of sacrificial supports, permanent support and temporary supports. The optimum ratio of the length over radius (L/R) for permanent supports is below or equal to 4.0, where for temporary supports below or equal to 10. The ratio is defined based on consideration of major deflection sources and torsion (angle of twist) (Boonsuk & Frank, 2009). For the tool selection, the minimum length of the tools must be equal to the depth of the machined surface at respective orientation. This is to ensure the machining processes are safe and to avoid the collision of tool holder with the indexer and workpieces. The main goal of tool selections is to use tools that capable to reach multiple complex surfaces with best accuracy results.

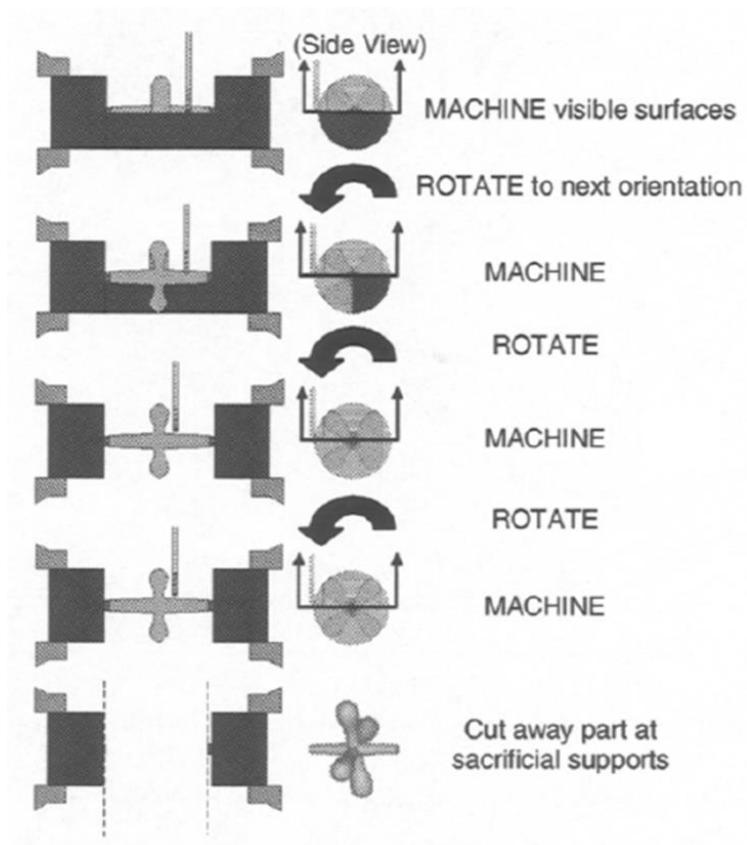


Figure 2.18 Rapid machining (RM) processing steps

Source: Frank (2004)

Ye Li (2006) presented a feature-free machinability analysis to determine optimum number of operation to completely machine parts with one axis of orientation setup. There are two types of analysis concept which is visibility and machinability. The main difference between these two concepts is the method of analysis. Visibility analysis utilizes a line of light to determine the cutting accessibility where machinability analysis considers size, cutting tool geometry and cutting orientation. In the study, the author employed Configuration-Space (C-Space) concept to perform the machinability analysis, which is the strategy of machining by using single axis of rotation for setup orientations. A basic fundamental of C-Space is to identify the best configurations for a moving mechanism in an environment surrounded by obstacles. The geometrical orientation that has a barrier prevents the cutter from reaching the surface is called “Obstacle-Space”. Obstacle Space is defined as the aggregate of all

unfeasible cutter locations with respect to an orientation due to the existence of an obstacle (Ye Li & Frank, 2006). C-Space concept will provide the safe space for tool path planning without any obstacles space. Therefore, tool path based on C-Space are always gouge-free and collision-free.

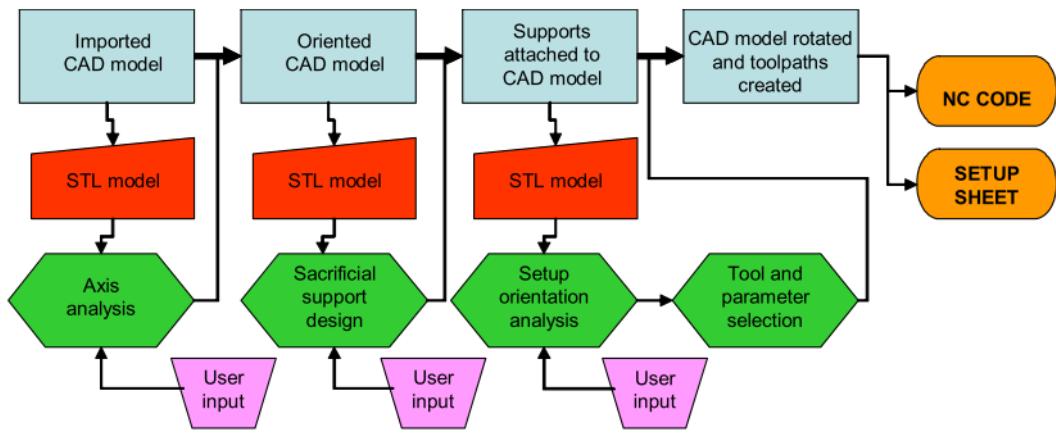


Figure 2.19 Interaction CAD model and CAM system through STL format

Source: Frank (2007)

A main challenge for the implementation of rapid prototyping in CNC machining (CNC-RP) is the skills of machinist consist of tool path planning, fixture planning and machining setup. Due to the issue, Frank (2007) established an advances algorithm to assist and simplify the process planning for CNC-RP by integrating with the CAD/CAM environment (Frank, 2007). In rapid machining, there has a few sequential operation involves in order to complete the process. Through the implementation of rapid machining within CAD/CAM system, its permits a practical automation for NC code generation directly from a CAD model. The flowchart of the developed system is illustrated in Figure 2.19. At the beginning, the developed system will execute an analysis and proposed the optimum rotation axis. Then sacrificial support will be attached to the parts model. The system then will determine the setup orientation on the proposed axis. After that, the user needs to select the tool and insert the required machining parameters before generating the tool path to start the machining processes. Based on these literature, the implementation of CNC-RP concepts in CAD/CAM environment is feasible to be utilized for custom fabrication, product prototyping and single run production.

Nafis (2014) have developed two approaches to accommodate the orientation proposed by the visibility analysis in roughing operations (Nafis et al., 2014). The first approach is proposing additional orientations for the roughing operation where the second approach is splitting and assigning the roughing operation to other independent orientations. Both approaches are basically conducted to discover the optimum roughing orientation angles. In order to machine the entire part surface, there is a need to determine the number of orientations required. The author proposed that the roughing operation must be executed with a minimum of three orientations in order to avoid thin webs and to preserve cutting tool life. Thin webs are thin layers of material that form on the machine parts due to material removed in opposite direction. With three cutting orientation approaches, the thin web formation can be avoided. An optimum roughing orientation angles also can be discovered through the simulation result. A customized coding was developed by using NX7.5 simulation software to simulate the machining based on the various tool angles. The output obtained from the studies are detailed machining times consist of roughing operation, finishing operation and non-cutting movements. The systems run automatically once the required inputs are provided. Nafis (2016) has extended the analysis in finishing operation for CNC-RM applications to identify the effects of using minimum two cutting orientations (Nafis, 2016). Previous finding, the author has suggested the separation of cutting orientation between roughing operation and finishing operation, thus the finishing operation become more independent and flexible. The finding in this study illustrates the positive effects of minimizing the number of orientation that manages to cut down the cutting times. However, the proposed method of using minimum two cutting orientation for finishing operation is only applicable for non-complex parts. For the complex parts, the visibility analysis is required where the cutting tools are not feasible to cater all surfaces within two cutting orientations.

The main factor that prohibiting computer numerically controlled (CNC) machining for being used as a rapid prototyping (RP) processes are labour-intensive and time-consuming task due to the manual process planning (Frank, Wysk, & Joshi, 2016). In order to cater the issue, Frank (2016) initiated an approach to create the tool path automatically and eliminate the complicated process planning within CNC machining.

The outcome of the research suggested a setup orientation from the visibility of slice geometry. It is much simpler to solve a series of 2D visibility problem because the accessibility is limited only to one rotation axis. Generally, visibility is based on “line-of-sight” to a surface and on the local geometry. In this study, the visibility algorithms were implemented in C program and a “Toy-Jack” is used as a tested model. Slice geometry files is entering as an input and several critical process parameters are obtain from the program, which are the minimum number of orientation, minimum stock diameter and the distance between minimum and maximum layer depth for each orientation. This method is a significant improvement over existing methods by modifies the representation of the slice geometry in effort to seek for a feasible visibility solution. A summary of the previous works is given in Table 2.3.

Table 2.3 Machining simulation model for cutting orientation

Authors	Year	Optimization		Research Outcomes	
		Objectives			
		Machining	Process		
		Time	Plan		
(Frank, 2004)	2004	x	x	Uses a layer-based approach for the CNC rapid machining of common parts geometries in variety material parts.	
(Ye Li, 2006)	2006		x	Propose machinability analysis approach for 3-axis flat end milling with single axis of rotation based on the concept of C-space.	
(Frank, 2007)	2007		x	Implement rapid machining system using CAD/CAM interface, enables automatic generation of process plan for machined component.	
(Nafis, 2014)	2014	x	x	Proposed additional orientation approaches and assign roughing operation to independent orientation.	
(Nafis, 2016)	2016	x	x	Identify the effects of using a minimum of two cutting orientations in finishing operations for non-complex parts.	
(Frank, 2016)	2016		x	The visibility data provides critical information for determining the minimum number and orientation of 2.5-D toolpaths required to machine the entire surface of a part.	

2.5.4 Cutting Parameter Simulation

Optimum selection of cutting conditions highly contributes to the increasing of productivity and decreasing of production cost. Cutting parameter simulation has become an essential process in manufacturing sectors. In machining processes, simulation of cutting parameter is considered a tool for improvement to obtain good quality parts and reduce process planning time (Deepak, 2012). A proper set up of cutting parameters will assist the machine to produce higher geometrical accuracy and good surface finish. During the cutting operations, amount of volume remove from raw material are crucial to produce the desired geometrical shapes (Radhika, 2015). CNC machining processes is well known as more expensive compare to others manufacturing processes such as forging or casting. Since the process required high capital cost, an economic operation is necessary in order to earn the return of investment. Generally, optimum machining operation is mainly depending on the proper selection of cutting parameter such as cutting speed, feed and depth of cut. The machining operation should be keep optimized to increase the quality of the part surface at minimum machining time with minimum process planning. Hence, a reliable simulation method should be developed in order to optimize the process. Besides, the dependency on experienced machinist to determine the cutting parameters can be minimized.

In 2011, experiments were conducted by Than Tun Aung to study the effect of radial and axial depth of cut on surface roughness in side milling operation. The unstable cutting tools conditions during machining operations are one of the major effects on quality of finished surfaces. The author has study in detail the correlation between radial depth of cut (RDOC) and axial depth of cut (ADOC) by dividing into two cases. The first case is machining operation with large RDOC and small ADOC, while the second case employs small RDOC and large ADOC. Through the analysis based on roughness data, it was found that the first case (large RDOC and small ADOC) produced higher surface roughness compare to the second case (small RDOC and large ADOC). Therefore, as a conclusion, machining with a small RDOC method can reduce the unstable cutting tool condition and also are able to produce a better machined surfaces.(Aung, 2011).

In 2012, Miko conducted a study to investigate the effect of ball end mill tool on surface roughness when machined free form surfaces. A cusp height on machined

surface is verified experimentally during finishing operation. There are few factors affecting the finished parts quality, one of the major factors are the condition of end mill tool such as tool edge geometry, tool performance and tool coating. The non-flat geometry of ball end mill cutter has restricted ability to from certain parts geometry. Therefore, the only way to produce a good surface finish is by controlling the RDOC distance value. Besides that, when the ball end mill tool moves on inclined surfaces, the tool edges formation can be seen on the machined surfaces due to the effective of cutting tool diameter. This effect consists of two elements, one is due to the axis of tool rotation (cusp bottom line) and another one is due to RDOC (true cusp height). These geometrical interpretations are illustrated in Figure 2.20. The scope of the research is to identify the effect of tool angle from surface normal onto surface roughness. A few of tool angle (2.9° , 11.5° , 20.4° , 30° and 36.9°) and milling angle direction (0° , 45° and 90°) are simulated with three different RDOC (0.2mm , 0.50mm and 0.80mm) (Figure 2.21). The author has drawn conclusions where the greater the angle of tool from surface normal, the better the surface finish. This is achieved by integration of the cutting tool edge with different cusp height.

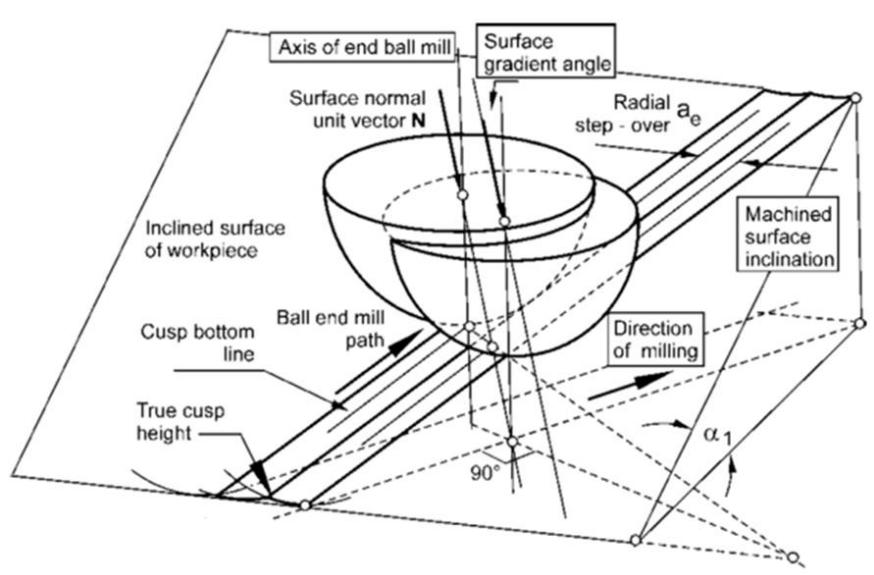


Figure 2.20 Geometrical interpretation of cusp formation on inclined surface
Source: Mikó, Beňo, & Maňková (2012)

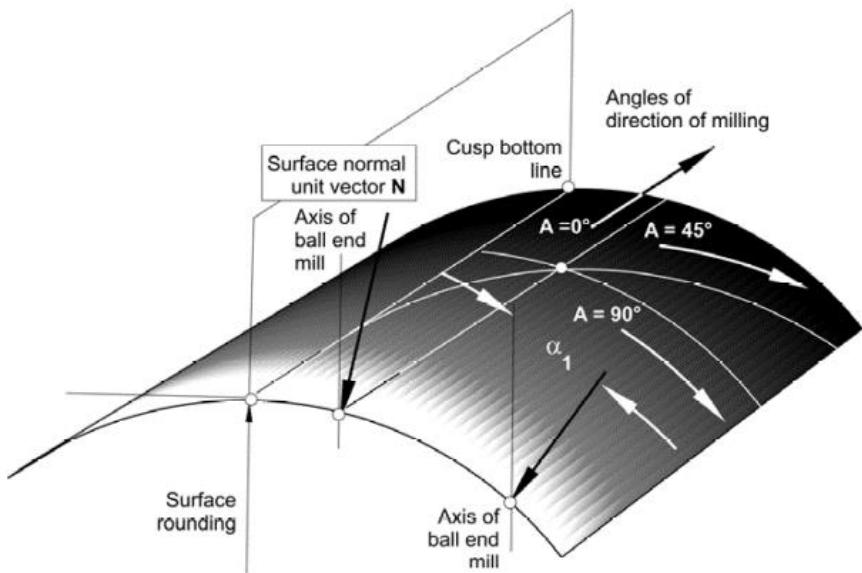


Figure 2.21 Semi-cylindrical surface and milling angle of direction

Source: Mikó et al. (2012)

In 2013, the surface roughness behaviour and trend has been studied by Bilek to identify the effect of dependent variable in terms of process parameter and surface quality. Due to the increasing demand for a good quality of product and production lead time, it is crucial to recognize the factors that influence production accuracy and surface quality. In CNC machining, the accuracy and quality of the part is directly related to the machinist experience and knowledge. Therefore, an accurate input for process parameter is important to obtain a good and high quality finished parts. In the study, the experiment has been divided into two groups. First experiment is to simulate the influences of shallow surface (15° inclination angle) and steep surface (75° inclination angle) on surface roughness with different value of radial depth of cut (RDOC). The input process parameter were radial depth of cut (RDOC) and surface inclination angle (α) as illustrated in Figure 2.22. Second experiment was aimed to investigate the influence of ball mill rake angle on surface roughness. The findings showed that radial depth of cut (RDOC) is the main parameter that affecting the quality of surface roughness when machined perpendicular into feed rate direction. The lower values of radial depth of cut (RDOC), the lower value of surface roughness was obtained, which indicate the best machined surface.

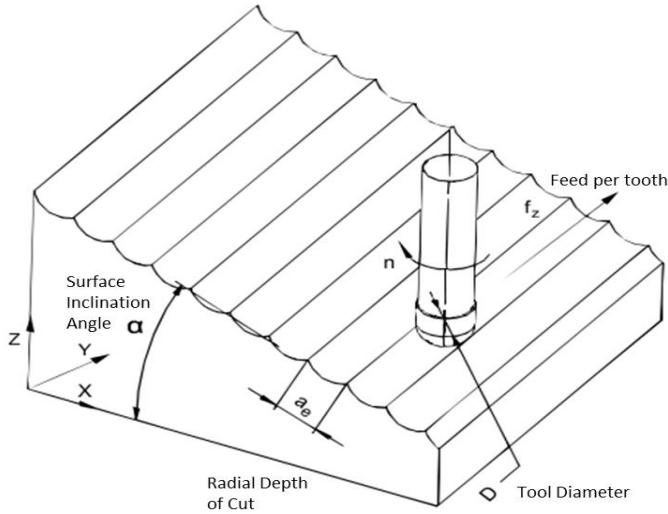


Figure 2.22 Illustration of the ball milling process

Source: Bilek, Sámek, & Suba (2013)

In 2014, cutting parameter optimization has been studied by Masmati focused on machined surface inclination angle, axial depth of cut (ADOC), spindle speed and feed rate. The aim is to investigate a better surface integrity in term of micro-hardness and residual stress. There have two aspects that can be explained by the definition of surface integrity, which are Topography Characteristic (surface roughness, waviness and flaw) and Surface-Layer Characteristic (hardness, cracks and residual stresses). In machining processes, the surface integrity is one of the factor that highly influenced by tool geometries and cutting parameter. The surface integrity of the product will be degraded if there is improper selection of cutting parameters. Nowadays, end milling machining is widely used in 2.5D operation which consist of roughing operation and finishing operation as shown in Figure 2.23. The 2.5D operation also known as ‘two and half axis mill’ where the cutting tools only move at 2 axes simultaneously, either on XY axis or XZ axis or YZ axis. While the cutting tools moving on +X and +Y direction, the depth of cut (-Z direction) remains constant until the cutting completed before it moves to the next assigned depth of cut. In roughing operation, a bulk of material were removed to produce a pre-shape of the product and finishing operation then take over to transform the pre-shape product into final finished parts and meet the acceptable tolerances. Experiment is conducted using Taguchi method to analyse the results and achieve the best control factor level. A main control factor was machined surface inclination angle (100° , 110° , 120°) and axial depth of cut (0.1mm, 0.25mm,

0.5mm). Based on the results, it was found that a residual stress and micro-hardness has greatly influenced by machine surface inclination angle, but axial depth of cut (ADOC) only affects the residual stress. The residual stress decreases (more tensile) and micro-hardness increases as machined surface inclination angle increases.

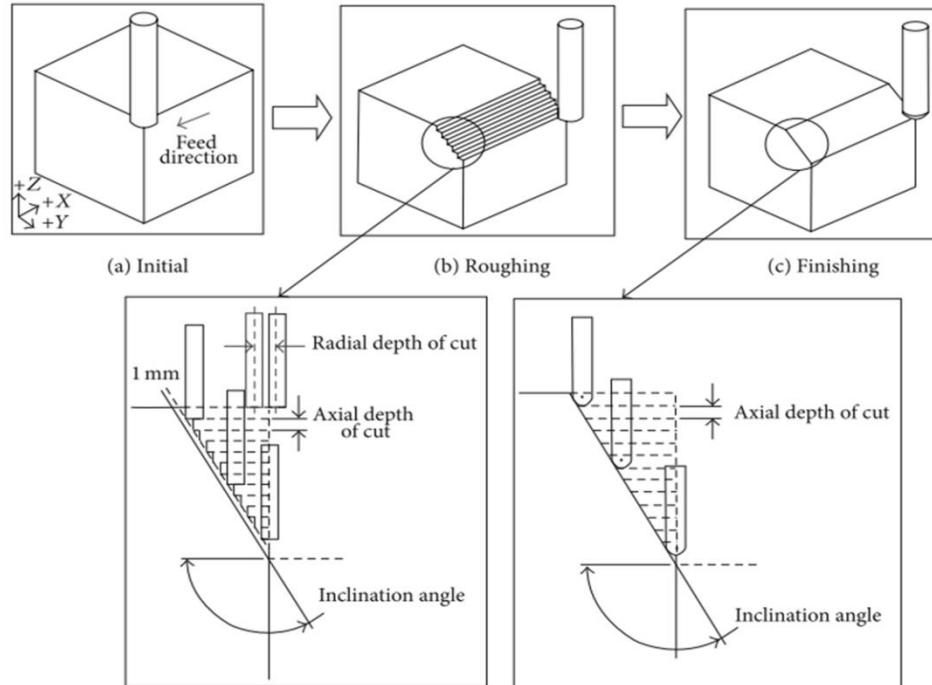


Figure 2.23 Illustration of machining operation

Source: Masmiahi (2014)

In 2015, Balazs has conducted an experiment to investigate the correlations between different free form surface condition (inclined and radius) on surface roughness by using ball end mil cutting tools. The qualities of the machined surface are closely related to cutting tools geometry and surface features. This is because the ball end mill tool has characteristic called an effective diameter, which will have different effects on different type of surfaces. In this experiment, a test workpieces has been prepared with 9 different surface conditions including flat surface, inclined surface and radius surface, as shown in Figure 2.24. 6 experimental samples were performed with different radial depth of cut (0.2mm, 0.5mm and 0.8mm) and feed rate (534mm/min, 890mm/min and 1246mm/min). Based on the analysis, feed rate does not affect the

machined surface quality, but it turns out to be affecting machining time. However, radial depth of cut (RDOC) is seen to have an impact on surface roughness on machined surfaces.

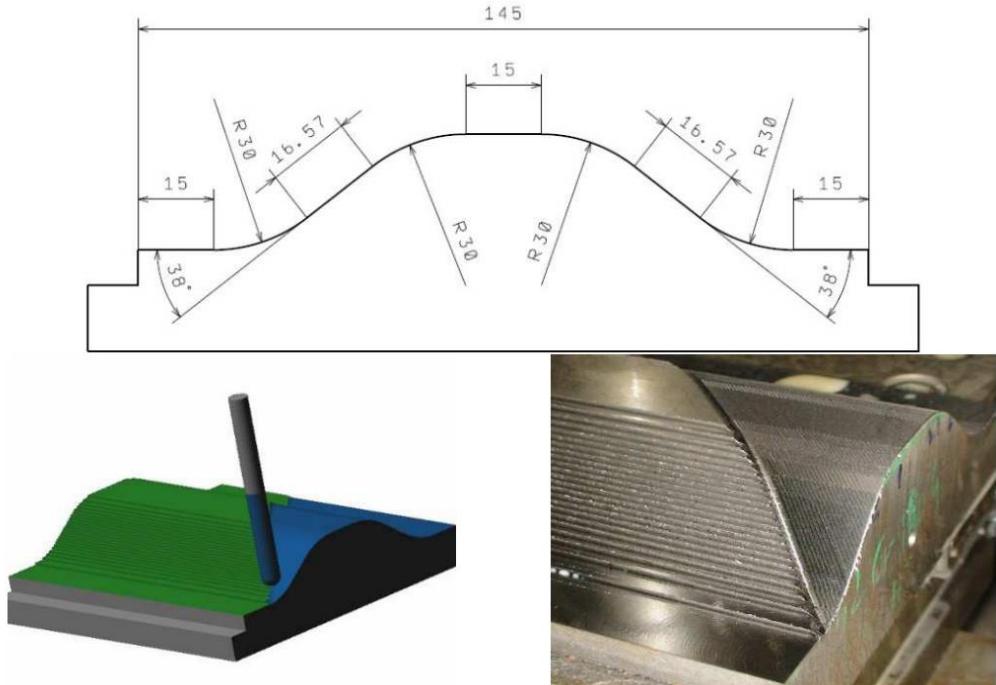


Figure 2.24 Different features on machine parts

Source: Balázs (2015)

Saikaew and Baowan in 2015 proposed a practical approach to determine the effect of machining time on surface roughness by using Design of Experiment (DOE) and Response Surface Method (RSM). The problem found when the ball nose end mill tool is being used for a long run, it tends to worn out and degrade the machine surface. The experiment is executed by manipulating four process parameters including spindle speed (RPM), feed per tooth (mm/tooth), axial depth of cut (mm) and radial depth of cut (mm) with two different levels for each parameter and five different cutting times. Results show that the surface finish of AISI P20 steel is good if optimum operating conditions (process parameters) were used. Besides, the tool life also can be significantly improved. Therefore, the cutting time issue to produce a good surface roughness was effectively solved by employing proposed DOE and RSM method (Saikaew & Baowan, 2015).

In 2016, Mikó has conducted an experiment to investigate the effect of different tool path strategy and cutting parameter on surface roughness. The main focus is 2.5D machining strategy with Z-level milling of steep surfaces. The Z-level milling was the optimal tool path in order to accurately machined steep surfaces (Kurt, Hartomac, Mutlu, & Köklü, 2012). The experiment is divided into two different cases (Test A and Test B) with different values of axial depth of cut (ADOC) (0.15mm, 0.20mm and 0.25mm), feed per tooth (0.08mm, 0.12mm and 0.16mm) and cutting direction (Climb and Zig-Zag). The parts used in the experiment has steep angle of 45° to 90° , as shown in Figure 2.25. Basically, the value of surface roughness can be derived theoretically from cusp height (Ch) calculation which consists of axial depth of cut (ADOC), cutting tool radius (R) and the angle of machined surface (α), as shown in Figure 2.26. However, in certain conditions, the calculation is not accurate due to the influence of other parameter in machining processes. Based on the analysis, it is found that the higher steep angle yields better surface roughness than the low steep angle. However, if the difference between axial depth of cut (ADOC) and feed per tooth value is small, then the steep angle does not affect the surface roughness. On the other hand, the increase of axial depth of cut (ADOC) and feed per tooth value will affects the surface roughness if the low steep angle is applied. Finally, cutting speed only has a slight impact on surface roughness.

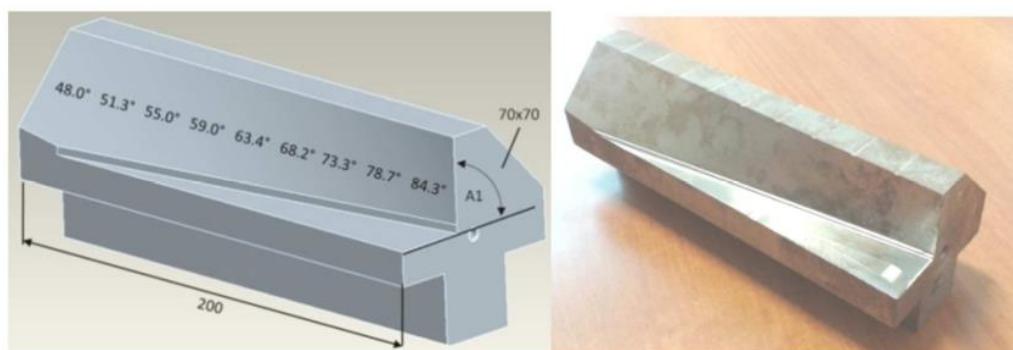


Figure 2.25 Part model with continuously steepness

Source: Mikó (2016)

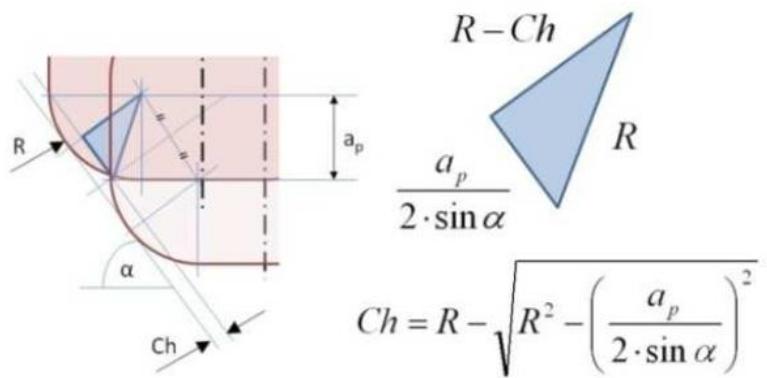


Figure 2.26 Cusp height (Ch) calculation

Source:(Mikó (2016)

In 2017, Razavykia conducted research to study the effect of tool path strategy on surface roughness for complex surfaces focusing in the medical industry. In the manufacture of orthopaedic implants, parts quality and machining time are very important factors to ensure that surgical work can be carried out more efficient and accurate. In the experiments, four specimens has been used with different cutting strategy consist of spiral outward, spiral inward, radial and zig-zag tool path as shown in Figure 2.27. The step over used for each simulation are 0.2mm except for radial tool path 0.4 degree due to different condition on tool path movement. The experiment assessments consist of surface quality, dimensional accuracy and machining time. Based on the simulation, it is proven that tool path strategy also has a great influence on machined parts quality a part of the cutting parameters. This can be observed in experimental results of surface roughness measurement with different tool path strategy. The spiral outward tool path strategy has showed lowest value of surface roughness, while zig-zag tool path strategy shows the highest value. Therefore, the zig-zag tool path strategy is not suitable for finishing operations because it will add extra time for polishing operations. In terms of dimensional accuracy, spiral outward also shows the highest deviations compared to three other machining strategies when measured on the X and Y-axis on the workpieces. Therefore, in this case, spiral outward capable to machine parts within required dimensional accuracy and highly recommended tool path for finishing operation. From the experiment, the machining time is measured to identify the correlation between tool path strategies and cutting operation. Usually in commercial CAM software, the machining times is calculated by dividing the total tool length with programmed feed rate. The result indicate a

significant difference of machining time recorded from CAM simulation and real machining. This is due to limitations on CNC machines, where the value of feed rate not always constant. Thus, the machining time are not able to be predicted accurately by CAM software (Coelho, De Souza, Roger, Rigatti, & De Lima Ribeiro, 2010).

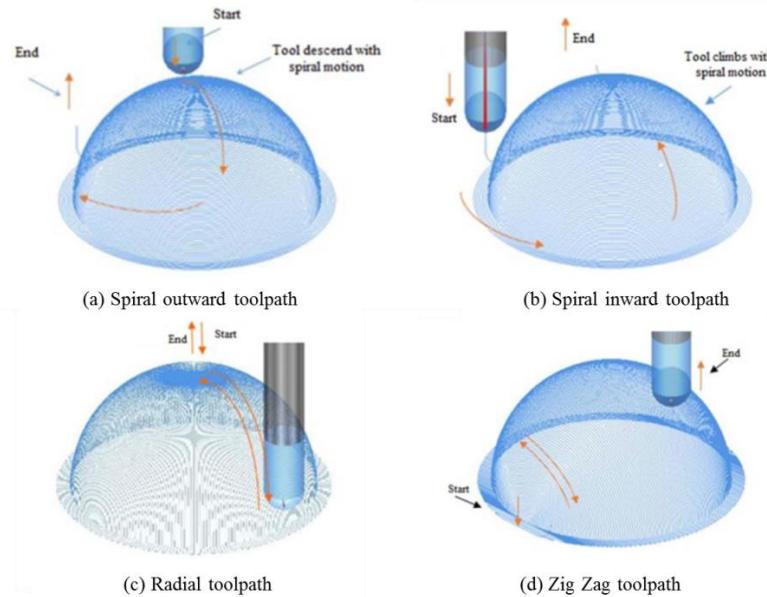


Figure 2.27 Toolpath simulations

Source: A. Razavykia (2017)

Balabokhin 2017 performed a study to investigate the best milling cutter among for different free-form surface zone in finishing operation. The study consists of two phases where the first phase is to determine the performance of each cutting tool for each cutter location point. Cutter location or namely CL-Data is the position of milling cutter in a CNC milling machine that received instructions from machining program (G-Code). Secondly, cutting tools that produce the best performance of each cutter location point are selected. The milling surface is divided into several zones with the optimum tool for each zone. There are few factors that influenced the cutter selection, such as production cost, cutting tool life, machined parts geometry, machining quality and accuracy. Figure 2.28 showed the schematic diagram of scallop height formation with constant step over during machining operation using different tools geometry and surface inclination. In a common practice, the surface quality obtained from the

machining process has correlations with machining scallop height. Step over (g) or radial depth of cut (RDOC) is defined as the distance between two adjacent tools along tool path direction while scallop height (h) is defined as the maximum height of un-machined material. Balabokhin (2017) has formulated several approaches to optimize the machining quality within acceptable geometric constraint and minimum production cost. The approaches were divided into four sections. The first part is to examine the logic and constraint criteria on the best cutter. The second part provides discretized representation models on parts and generalized cutters. The third part is to generate simulations of algorithm adaptations for selected models (Figure 2.29). The fourth part is to provide the performance analysis based on graphics processing unit (GPU) implementation. Through the proposed approaches, the best cutting tools for each different surface zone has been determined more effectively and managed to minimize cutting time.

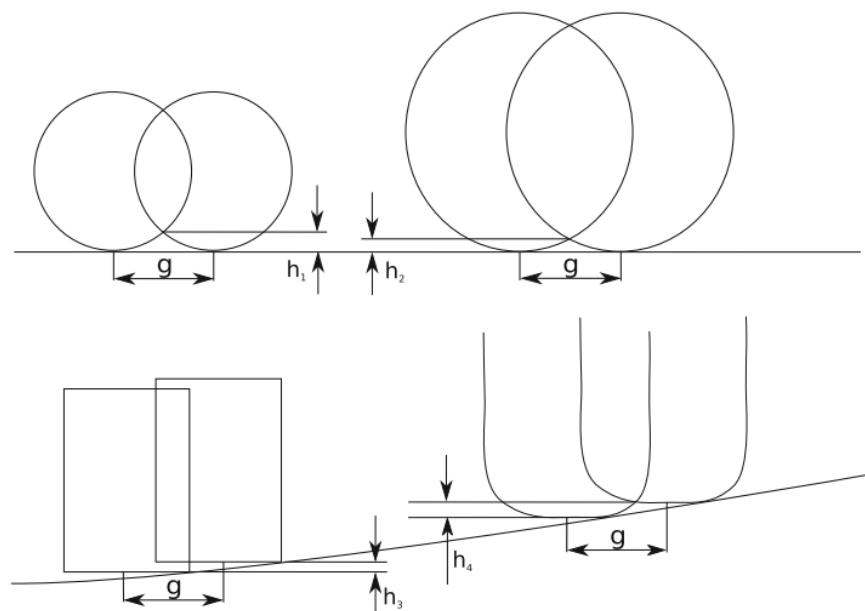


Figure 2.28 Schematic of scallop formation: step over (g) and scallop height (h)

Source: Balabokhin & Tarbutton (2017)

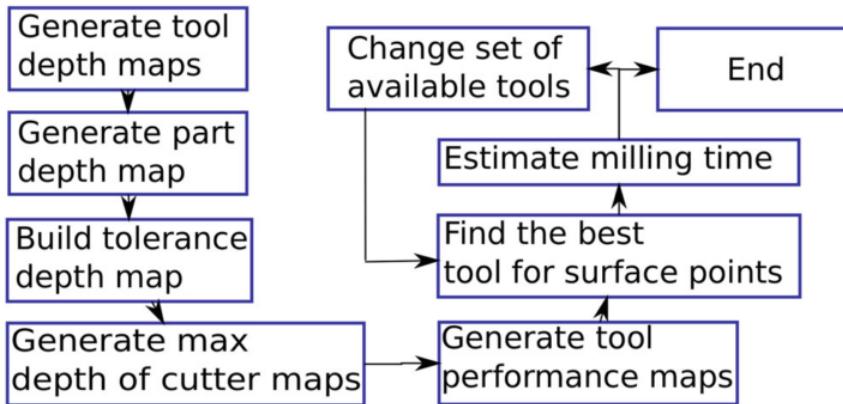


Figure 2.29 Algorithm simulation flow

Source: Balabokhin & Tarbutton (2017)

Miko 2017 conducted a comparison study between theory and real surface roughness on the plain surface of 42CrMo4 steel material. In general, surface roughness can be assessed theoretically by calculations based on cusp height. The cusp height calculation basically consists of ball mill tool diameter, tool path direction and machined surface inclination (Mikó et al., 2012). However, in real machining, there might have some other external factors that need to be considered which can affect the surface quality. The aim of the study is to investigate the effect of machining cutting condition towards surface quality by using ball mill tool. Three cutting parameter input variable was manipulated which is Axial depth of cut (ADOC), Radial depth of cut (RDOC) and the feed per tooth (fz). The full factorial design of experiment method (DOE) was employed to run experiments with 3 different levels of predetermined parameters, ADOC (0.1mm, 0.25mm, 0.4mm), RDOC (0.10mm, 0.25mm, 0.4mm) and feed per tooth (0.02 mm/tooth, 0.05 mm/tooth, 0.08 mm/tooth). Based on analysis, it was found radial depth of cut (RDOC) and axial depth of cut (ADOC) parameter are the major factor that affecting surface roughness while feed per tooth (fz) is not significantly affect (Mikó, Tóth, & Varga, 2017).

Previous researchers have conducted a lot of machining simulation analysis focusing on accuracy and surface quality. In order to perform the analysis, various optimization approaches and techniques are used. However, most of the simulations are focusing on common process parameters such as spindle speed, feed rate and depth of cut. To date, there is no simulation methods established to analyse and optimise the

ADOC and RDOC parameters particularly in 4 axis machining application. Hence, the work presented here make an attempt to improvise the simulation routines and aim to minimize process planning, obtain a higher machined parts accuracy and acceptable surface roughness. A summary of the previous work is given in Table 2.4.

Table 2.4 Finishing machining parameter simulation

Author /Year	Process Parameter	Machine	Material	Machining Performance
(Aung, 2011)	- Radial depth of cut (mm) - Axial depth of cut (mm) - Feed Rate (mm/min) - Feed per tooth (mm/tooth)	3 Axis DMC 105V linear milling machine	HRB mild steel plates	Surface roughness
(Mikó <i>et al.</i> , 2012)	- Radial depth of cut (mm) - Feed Direction Angle (°) - Tool Angle (°)	3 Axis Mazak Nexus 410A-II milling machine	42CrMo4 steel	Surface roughness
(Bilek <i>et al.</i> , 2013)	- Radial depth of cut (mm) - Surface inclination angle (°) - Feed per tooth (mm/tooth) - Tool rake angle (°)	3 Axis Vertical milling machine Mikron HSM	Stainless Steel X153Cr MoV12-	Surface roughness
(Masmiati <i>et al.</i> , 2014)	- Axial depth of cut (mm) - Surface inclination angle (°) - Spindle speed (RPM) - Feed rate (mm/min)	5 Axis SPINNER U- 620 CNC milling machine	S50C Medium Carbon Steel	Micro-Hardness Residual Stress

Table 2.4 Continued

Author /Year	Process Parameter	Machine	Material	Machining Performance
(Balázs, 2015)	- Radial depth of cut (mm) - Feed rate (mm/min)	3 Axis MAZAK 410A-II CNC millling machine	EN ISO 42CrMo 4 (1.7225)	Surface Roughness
(Saikaew <i>et al.</i> , 2015)	- Radial depth of cut (mm) - Axial depth of cut (mm) - Spindle Speed (RPM) - Feed per Tooth (mm/tooth)	3 Axis MIKRON VCE 750 CNC milling machine	AISI P20 steel	Surface Roughness Machining Time
(Mikó, 2016)	- Axial depth of cut (mm) - Feed per tooth (mm/tooth) - Cutting Steep Angle (°)	4 Axis MAZAK 410A-II CNC millling machine	S355 low alloyed structure 1 steel	Surface Roughness
(A. Razavykia, A. Esmaeilzad eh, 2017)	Machining Strategy: - Spiral outward - Spiral inward - Radial - Zig-zag	3 Axis MAHO MH700 S vertical milling machine	Stainless Steel 316L	Surface Roughness Dimensional Accuracy Machining Time
(Balabokhi <i>n et al.</i> , 2017)	- Cutting Tool Geometry	3 Axis Milling Machine	-	Machining Time Surface Roughness

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter provides detail discussion on the methodology implemented in this research in terms of the machining simulation program development and execution of machining operation. First section of this chapter explains the overview of proposed simulation framework, which later used to execute the simulation routines. Next sections explain the fundamentals of proposed simulation program, consist of integration and customization of NX CAM instruction code with VB script and development of Graphical User Interfaces (GUI) for front-end user. Two simulations program were developed which is “RoughSimulCAM” for roughing operation and “FinishSimulCAM” for finishing operation. Each program executes different simulation routines and operation analysis. The next section explains the machining simulation process planning and verification method to analyse the simulation outcomes. Figure 3.1 shows tools and equipment that are identified to perform the simulation. These include NX CAM package, Microsoft Visual Basic and 3 Axis CNC machine with indexing devices. The aim of the studies is to develop machining simulation program and generate an optimal parameter for cutting orientation and cutting parameter in 4 axis machining routines

In this study, the machining simulations is executed based on two types of operation; roughing and finishing operation. In roughing operation, different cutting tool orientation was simulated, where each orientation set possessed different direction which later implicates the total time consumed to completely machine the part. For this study, the cutting tools angle is manipulated from 0° to 360° with 5° step over. The cutting orientation is programmed with three different set. First set with three orientations (0° - 120° - 240° and 0° - 135° - 225°) and second set with four orientations (0° - 90° - 190° - 270°). The simulation routines are used to analyse which orientation set possesses maximum volume removed in roughing operation. Volume removed

assessment calculated by using Vericut, which is an advanced software for simulation and analysis of workpiece, toolpath optimization and machining simulation (Zhou et al., 2019) (Guoyan, Rongcheng, Weifeng, & Jinguo, 2019) (Ye, Yin, Cai, & Xu, 2020). The highest volume removed from roughing simulation is denoted as an optimal cutting orientation. On the other hand, in finishing operation, a correlation between radial depth-of-cut (RDOC) and axial depth-of-cut (ADOC) is simulated simultaneously. The value of cutting parameters used is in percentages form, where it is based on the allowable range value permitted for each parameter (Dapra, 2018). For RDOC values, the value ranges used is from 5% to 45% of the cutting tool diameter, while for ADOC values ranging from 2% to 10% of tool diameter. Each parameter value is paired in opposite order and there has 9 set of parameter input values will be entered into the programming interface. The highest volume removed from finishing simulation is denoted as the optimum cutting parameter. Figure 3.2 shows the research methodology framework.

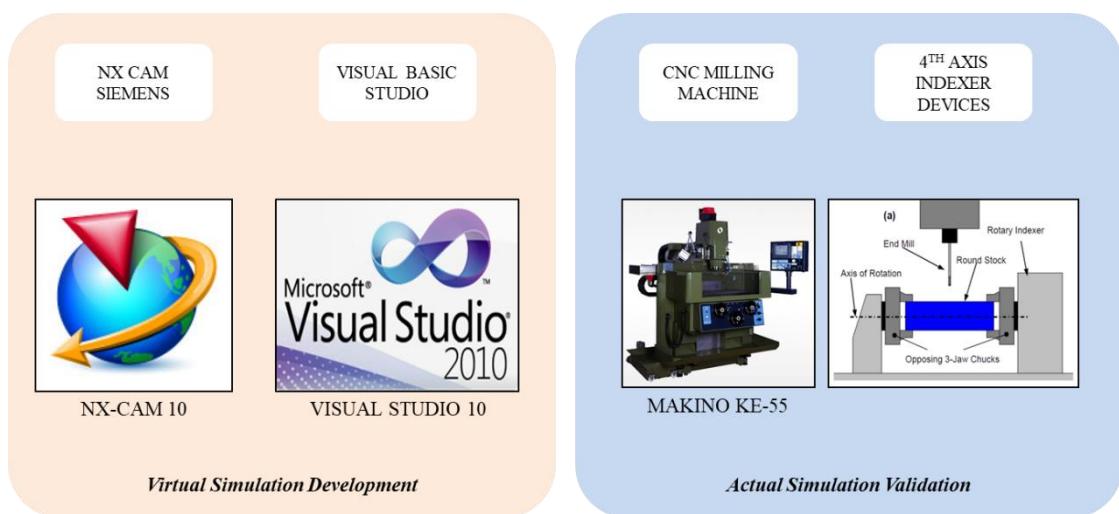


Figure 3.1 Software environment and machine tools

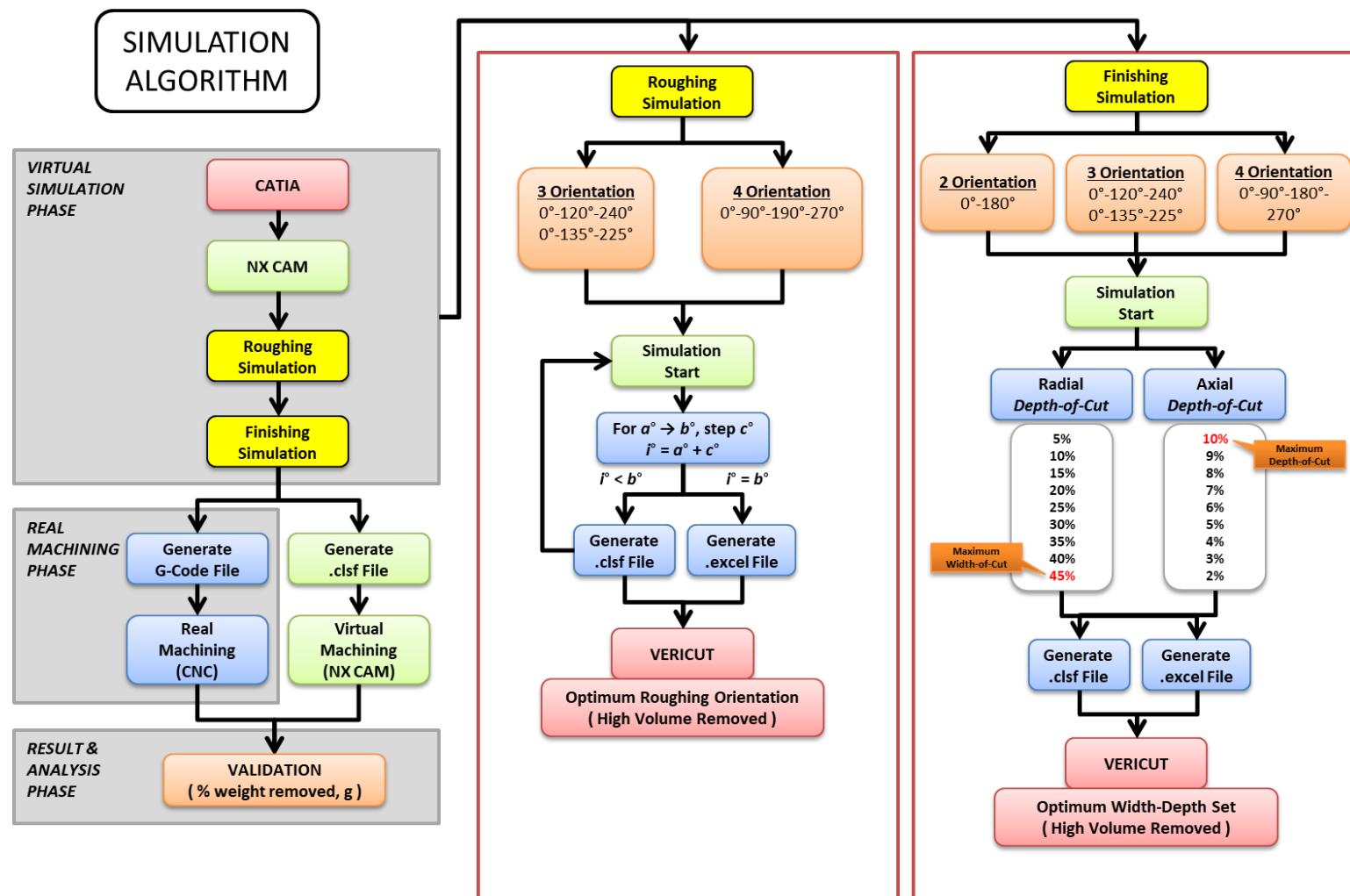


Figure 3.2 Research methodology framework

3.2 Development of Simulation Program

3.2.1 Simple NX Applications Programming (SNAP)

Simple NX Applications Programming (SNAP) is known as Application Programming Interfaces (API) that allows a NX user to customize and develop a custom program to extend NX function. There are few advantages that can be explored through SNAP, one of the benefit is the program offer a method to speed up a repetitive tasks and capture important process design during simulation development. SNAP was designed to assist NX user with little or no experience and knowledge about programming. It helps them to quickly learned and manipulate the instruction to perform certain simulation tasks. Therefore, NX user can improvise their simulation efficiency and productivity without need a lot of time to understand the simulation function (Siemens, 2014). SNAP is based on NX open programming and can be integrated smoothly through visual basic programming.

3.2.2 NX Journaling

In NX system, there has an interactive recorder function, known as Journaling function. This functions are used to translate NX user interactions into journal code, either Visual Basic or C++ language. Journal file can be customized and manipulated by using standard functions. The journal function is activated through Developer tab, as shown in Figure 3.4, in NX main manufacturing application interface (Figure 3.3). The 3D model that has been designed should be opened before start the journal recording process. To activate the recording, ‘Record’ button is pressed then a machining simulation program is developed by NX user through a series of steps using standard function in manufacturing applications. Journal file is like a log file, which will store all the memory into text file from every tool and function that has been used by NX user, as shown in Figure 3.5. During the recording, every step and parameter set to the machining simulation will be recorded and indexed into the journal file. This allows the NX user to modify the data and develop customized machining simulation program. Once the instruction to construct machining operations completed, the journal recording mode is ended by pressing ‘Stop Recording’ button. An ‘Edit’ button allows NX user to view the previously recorded journal files and make changes to the recorded codes

accordingly. A detailed step of machining simulation program development will be discussed in the next sub-chapter.

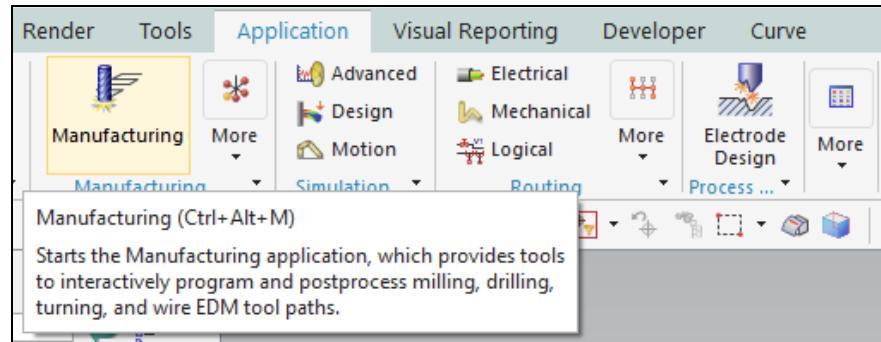


Figure 3.3 Main manufacturing application interfaces

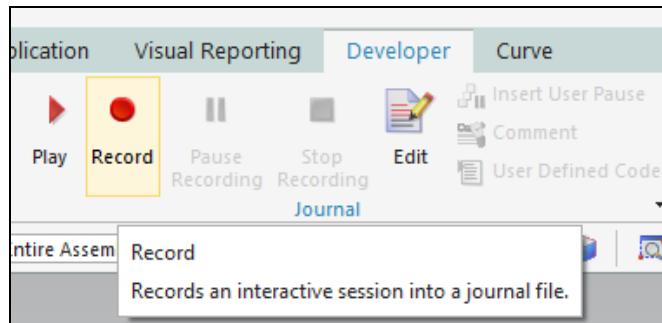
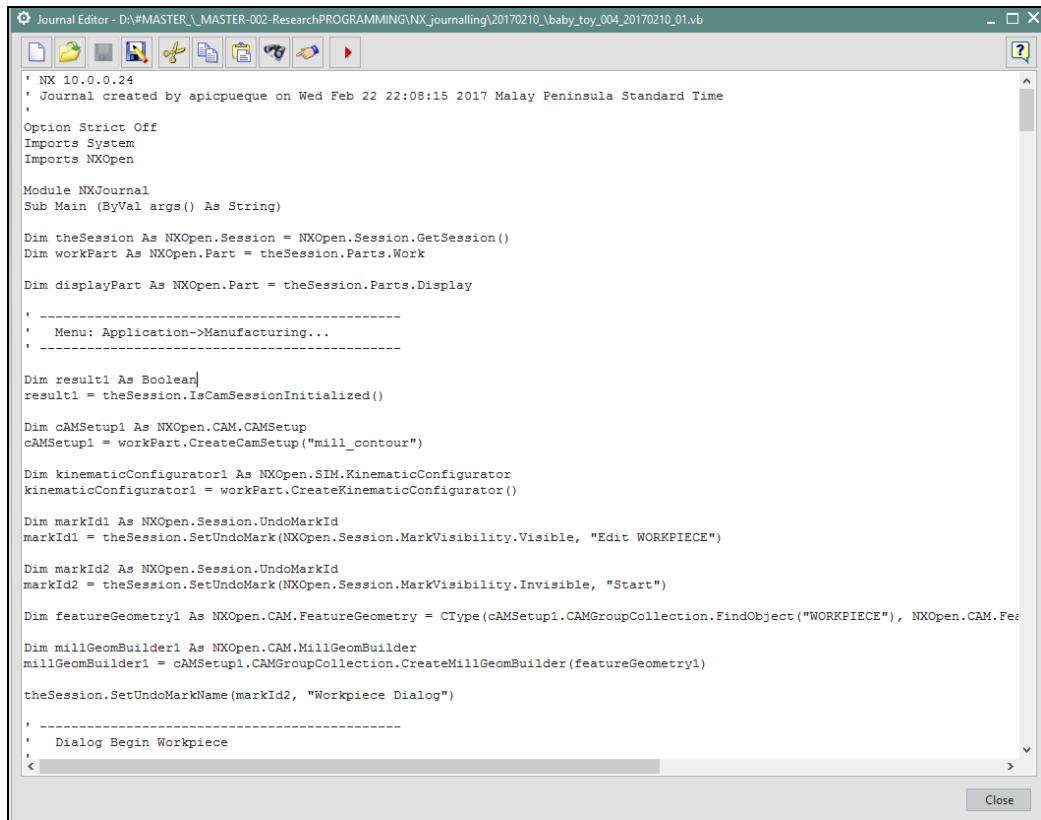


Figure 3.4 Journaling record activation



The screenshot shows a Windows application window titled "Journal Editor - D:\#MASTER_\MASTER-002-ResearchPROGRAMMING\NX_journailling\20170210\baby_toy_004_20170210_01.vb". The window contains a code editor with Visual Basic script. The code is as follows:

```

' NX 10.0.0.24
' Journal created by apicqueue on Wed Feb 22 22:08:15 2017 Malay Peninsula Standard Time
'
Option Strict Off
Imports System
Imports NXOpen

Module NXJournal
Sub Main (ByVal args() As String)

Dim theSession As NXOpen.Session = NXOpen.Session.GetSession()
Dim workPart As NXOpen.Part = theSession.Parts.Work

Dim displayPart As NXOpen.Part = theSession.Parts.Display

' -----
'   Menu: Application->Manufacturing...
' -----

Dim result1 As Boolean
result1 = theSession.IsCamSessionInitialized()

Dim cAMSetup1 As NXOpen.CAM.CAMSetup
cAMSetup1 = workPart.CreateCamSetup("mill_contour")

Dim kinematicConfigurator1 As NXOpen.SIM.KinematicConfigurator
kinematicConfigurator1 = workPart.CreateKinematicConfigurator()

Dim markId1 As NXOpen.Session.UndoMarkId
markId1 = theSession.SetUndoMark(NXOpen.Session.MarkVisibility.Visible, "Edit WORKPIECE")

Dim markId2 As NXOpen.Session.UndoMarkId
markId2 = theSession.SetUndoMark(NXOpen.Session.MarkVisibility.Invisible, "Start")

Dim featureGeometry1 As NXOpen.CAM.FeatureGeometry = CType(cAMSetup1.CAMGroupCollection.FindObject("WORKPIECE"), NXOpen.CAM.Fe
Dim millGeomBuilder1 As NXOpen.CAM.MillGeomBuilder
millGeomBuilder1 = cAMSetup1.CAMGroupCollection.CreateMillGeomBuilder(featureGeometry1)

theSession.SetUndoMarkName(markId2, "Workpiece Dialog")

' -----
'   Dialog Begin Workpiece
' <

```

Figure 3.5 Sample of recorded journal file

Figure 3.6 shows a brief overview of process flow on how the customization process is developed in NX CAM system through journaling function. This is the first chart that illustrate the overall framework of the journaling processes while the following flow charts goes more detail according to different simulation program and code customizations. Orange box colour indicates action performed in development phase while grey box colour indicates action performed in application phase. The process starts with activating NX CAM software and imports the designated 3D model into the system or the user can design a new model. Next, construct and simulate machining program in NX-CAM while all the activities were recorded using Journal tools. After completed simulate machining operation, Journal recording stopped. A recorded journal files then is customized in Visual Basic Programming and finally proceed to development phase of Graphic User Interfaces (GUI) for machining simulation programs.

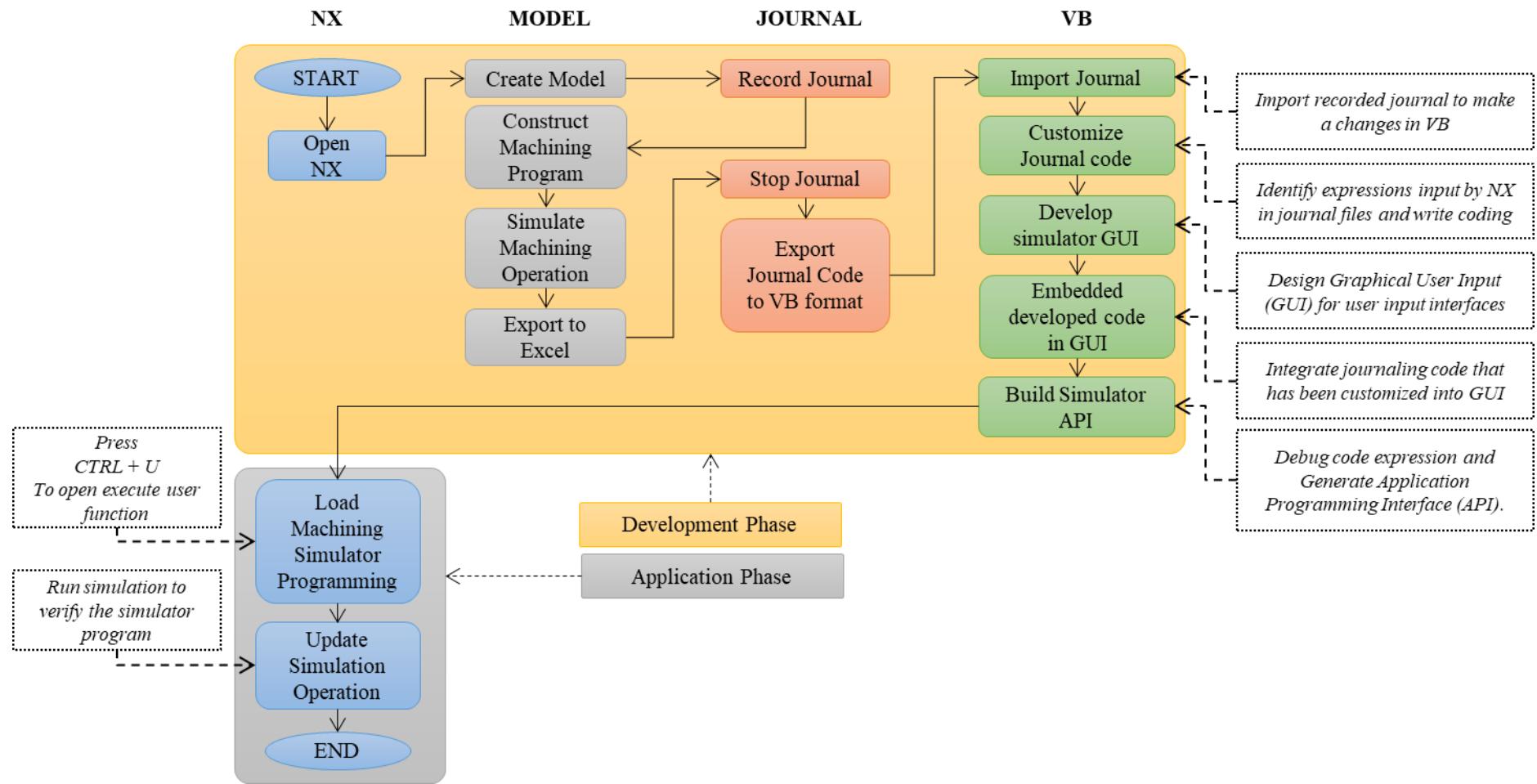


Figure 3.6 Journaling and code customization procedure

3.2.3 Code Customization and Development

Basically, there are four approaches in the source codes customization process, which are Grouped Code, Replacement Code, Simulation Instruction Code and Data Exportation Code. Grouped Code methods are used to simplify the code customization task by associating all variables that share the same values from user inputs. Therefore, one parameter value from user input can be used for many functions behind the simulation program code. Figure 3.7 shows the example of Grouped Code method for “workpieces diameter” input parameter. The values of workpieces diameter are useful to determine range depth of cut level and cut area extension distance. In developed programs, workpieces diameter is represented as “workpiecediameter” and consistently used for entire customized code.

The figure displays three code snippets from a Microsoft Word document, each enclosed in a rectangular box. The first snippet is located in the 'Form3_Load' event handler. It sets the text of three text boxes: 'workpiecediameter' to "50", 'orientationR01' to "0", 'RoughT001' to "10", and 'depthofcut01' to "2.0". The second snippet is part of a larger block of code under a dashed-line comment '----- Dialog Begin Cut Levels roughing01 -----'. It initializes a 'cavityMillingBuilder2.CutLevel.RangeType' to 'NXOpen.CAM.CutLevel.RangeTypes.Single' and then sets two 'SetRangeDepth' properties: one to 35.0 and another to '(workpiecediameter.Text / 2)'. The third snippet is part of a larger block of code under a dashed-line comment '----- Dialog Begin Cutting Parameters -----'. It sets the 'CutOrder' of 'cavityMillingBuilder2.CutParameters' to 'NXOpen.CAM.CutParametersCutOrderTypes.DepthFirst' and then sets the 'CutAreaExtensionDistance.Value' to 'workpiecediameter.Text' and its 'Intent' to 'NXOpen.CAM.ParamValueIntent.PartUnits'.

```
Private Sub Form3_Load(sender As System.Object, e As System.EventArgs) Handles MyBase.Load
    workpiecediameter.Text = "50"
    orientationR01.Text = "0"
    RoughT001.Text = "10"
    depthofcut01.Text = "2.0"

    '----- Dialog Begin Cut Levels roughing01 -----
    cavityMillingBuilder2.CutLevel.RangeType = NXOpen.CAM.CutLevel.RangeTypes.Single
    'cavityMillingBuilder2.CutLevel.SetRangeDepth(0, 35.0, NXOpen.CAM.CutLevel.MeasureTypes.TopLevel)
    cavityMillingBuilder2.CutLevel.SetRangeDepth(0, (workpiecediameter.Text / 2), NXOpen.CAM.CutLevel.MeasureTypes.

    '----- Dialog Begin Cutting Parameters -----
    cavityMillingBuilder2.CutParameters.CutOrder = NXOpen.CAM.CutParametersCutOrderTypes.DepthFirst
    cavityMillingBuilder2.CutParameters.CutAreaExtensionDistance.Value = workpiecediameter.Text 'roughing01
    cavityMillingBuilder2.CutParameters.CutAreaExtensionDistance.Intent = NXOpen.CAM.ParamValueIntent.PartUnits
```

Figure 3.7 Grouped code method

The original recorded code is specifically representing the model or part used during the journaling procedure. Therefore, the codes are sticky or only specific to the parts and not able to be used for other parts that have different features. In order to make the code become universal and applicable to various models, the code stickiness should be removed and replaced with a new functional code by using Replacement Code method. The new replacement code provides a function where it will generate window selection pop-up and allow user to directly select any model to perform

simulation task. Figure 3.8 shows the code stickiness replacement process that has been embedded in the simulation program.

```

'----- Dialog Begin Part Geometry -----
Dim partLoadStatus1 As NXOpen.PartLoadStatus
partLoadStatus1 = workPart.LoadThisPartFully()

partLoadStatus1.Dispose()
'=====

Dim bodies1(0) As NXOpen.Body
Dim body1 As NXOpen.Body = CType(workPart.Bodies.FindObject("UNPARAMETERIZED_FEATURE(0)", NXOpen.Body)
bodies1(0) = body1

Dim bodyDumbRule1 As NXOpen.BodyDumbRule
bodyDumbRule1 = workPart.ScRuleFactory.CreateRuleBodyDumb(bodies1, True)
'=====

Dim mySelectedParts() As NXObject
Dim myPlanarParts As New List(Of Body)

If SelectParts("", mySelectedParts) = Selection.Response.Cancel Then
    Exit Sub
End If

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

Dim bodyDumbRule1 As NXOpen.BodyDumbRule
bodyDumbRule1 = workPart.ScRuleFactory.CreateRuleBodyDumb(myPlanarParts.ToArray)
'=====

```

Figure 3.8 Replacement code method for stickiness removal

The simulation routines in this program will be carried out continuously, where the user only needs to enter the input once at the start of the operation. The program will execute the simulation operation accordingly, based on codes instruction embedded inside the program. Figure 3.9 shows the simulation instruction code in the RoughSimulCAM program, where the program used to simulate the roughing operation with different cutting orientation. Referring to the codes, variable 'a', 'b' and 'c' are used to bring the information from user input (textbox.text) to the simulation instruction code. Variable 'a' denoted as first cutting orientation, variable 'b' denoted as last cutting orientation and variable 'c' denoted as orientation step value between 'a' and 'b'. Throughout the simulation, the program will record the cutting length and cutting time value then export the captured data into Excel Files format. Once the simulation completed, the excel files that contains simulation data will automatically pop-up on the window screen.

```

    Private Sub roughing4simulation()
        Dim a As Integer
        Dim b As Integer
        Dim c As Integer

        Dim totalCuttingLength As Double
        Dim totalCuttingTime As Double
        Dim MRR As Double

        Dim saveData(360, 4) As Double
        Dim cData As Integer = 1

        a = textbox1.Text
        b = textbox2.Text
        c = textbox3.Text

        For nilai As Integer = a To b Step c
            roughing4_tekan(nilai, totalCuttingLength, totalCuttingTime, MRR)

            saveData(cData, 1) = nilai
            saveData(cData, 2) = totalCuttingLength
            saveData(cData, 3) = totalCuttingTime
            saveData(cData, 4) = MRR * totalCuttingTime

            System.Threading.Thread.Sleep(1000)
            Application.DoEvents()

            cData = cData + 1
        Next
        WriteValueToExcel_roughing4(cData, saveData)

        Me.Close()
        Form1.Close()
    End Sub

```

Figure 3.9 Simulation instruction code for RoughSimulCAM

For the second program, it uses similar approach but with different coding. FinishSimulCAM used to simulate the finishing operation with different axial depth of cut and radial depth of cut parameter. The program executes 9 simulation operations with various set of parameters. Figure 3.10 shows the simulation instruction code in the FinishSimulCAM program. Based on the code, the simulation is arranged according to the order of the experiment to be carried out, starting from experiment number 1 until experiment number 9. Each set of simulation has been embedded with a different depth of cut value based on input from the user. The program will develop a complete machining operation first (PlanarFreeFormSimulation) to form an operation framework. Then, it will execute all simulation routines according to the order stated in green box. Once all the simulation completed, the program will produce Excel Files format contains simulation result data and automatically pop-up on the window screen.

```

Private Sub PlanarFreeFormWidthDepthSimulation()
    PlanarFreeFormSimulation()
    PlanarFreeForm_experiment1(totalCuttingLength1, totalCuttingTime1)
    PlanarFreeForm_experiment2(totalCuttingLength2, totalCuttingTime2)
    PlanarFreeForm_experiment3(totalCuttingLength3, totalCuttingTime3)
    PlanarFreeForm_experiment4(totalCuttingLength4, totalCuttingTime4)
    PlanarFreeForm_experiment5(totalCuttingLength5, totalCuttingTime5)
    PlanarFreeForm_experiment6(totalCuttingLength6, totalCuttingTime6)
    PlanarFreeForm_experiment7(totalCuttingLength7, totalCuttingTime7)
    PlanarFreeForm_experiment8(totalCuttingLength8, totalCuttingTime8)
    PlanarFreeForm_experiment9(totalCuttingLength9, totalCuttingTime9)
    WriteValueToExcel_planarfreeform()
    Me.Close()
    Form1.Close()
End Sub

```

Figure 3.10 Simulation instruction code for FinishSimulCAM

3.2.4 Graphical User Interface (GUI)

Graphical User interface (GUI) allow the user to interact with the program where a specific function and control are embedded inside the program through visual indicators (McKeown, 2010). The purpose of GUI development is to improve the efficiency of process planning and reduce time to develop a program. GUI can ensure the simulations with repeated processes will provide consistent results as all the settings and parameters are well integrated inside the program. GUI uses to provide a platform where the users with minimum knowledge of programming are able to interact and retrieve information from the system. In order to assist the process planning task in machining simulation, several customized Graphical User Interface (GUI) are developed in this study.

3.3 Machining Simulation

3.3.1 CAD model preparation

Selection of parts to be machined is one of the factor that need to be taken into consideration before proceed with the machining simulation. In this research, Several CAD models are identified to be tested on the simulation application accordingly. Figure 3.11 shows elements required for CAD model before proceed to the simulation analysis. These requirements are derive based on the established methodology to perform rapid manufacturing through 4 axis machining operations (Frank, 2004). There are four main component consist of check block, sacrificial support, workpieces and model. Check Block is a two cylindrical component that are added on the both end of the workpieces with same diameter size. There are two functions of this component, first, to set the limit for cutting tool movement in parallel direction with workpieces. Second, represent as the clamping area for indexing device which reflect real machining setup. Sacrificial Support is a small cylindrical component act as a support to hold the parts from falling down after completing the machining processes (Boonsuk and Frank, 2009). The support will be removed once machining completed and, considered as post-processes. The main objective to add this support is to enable the cutting operations to be executed continuously without relocating the machined parts coordinate system. This support is connected with check blocks, which indirectly connected to the workpieces that clamped on the indexing devices. Next components for CAD model preparations are workpieces and parts model. The workpieces diameter size must be equal to the diameter of check block. Meanwhile, the length of the workpieces is a summation of length of parts and the length of the sacrificial support.

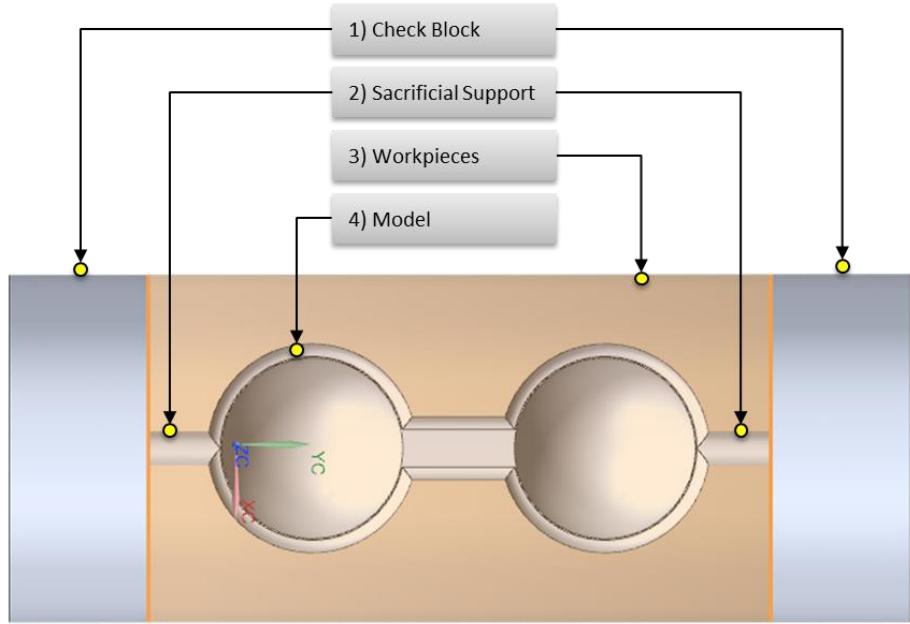


Figure 3.11 CAD model preparation requirement

3.3.2 Simulation Process Planning

Primarily, there are two main operation executed in machining simulation. Each operation possessed different approach in terms of simulation routines. RoughSimulCAM execute an analysis to determine an optimum cutting angle for roughing operation. FinishSimulCAM execute an analysis to determine an optimum cutting parameter (axial and radial depth of cut) for finishing operation. The summary of process planning for RoughSimulCAM and FinishSimulCAM machining simulation is shown in Figure 3.12.

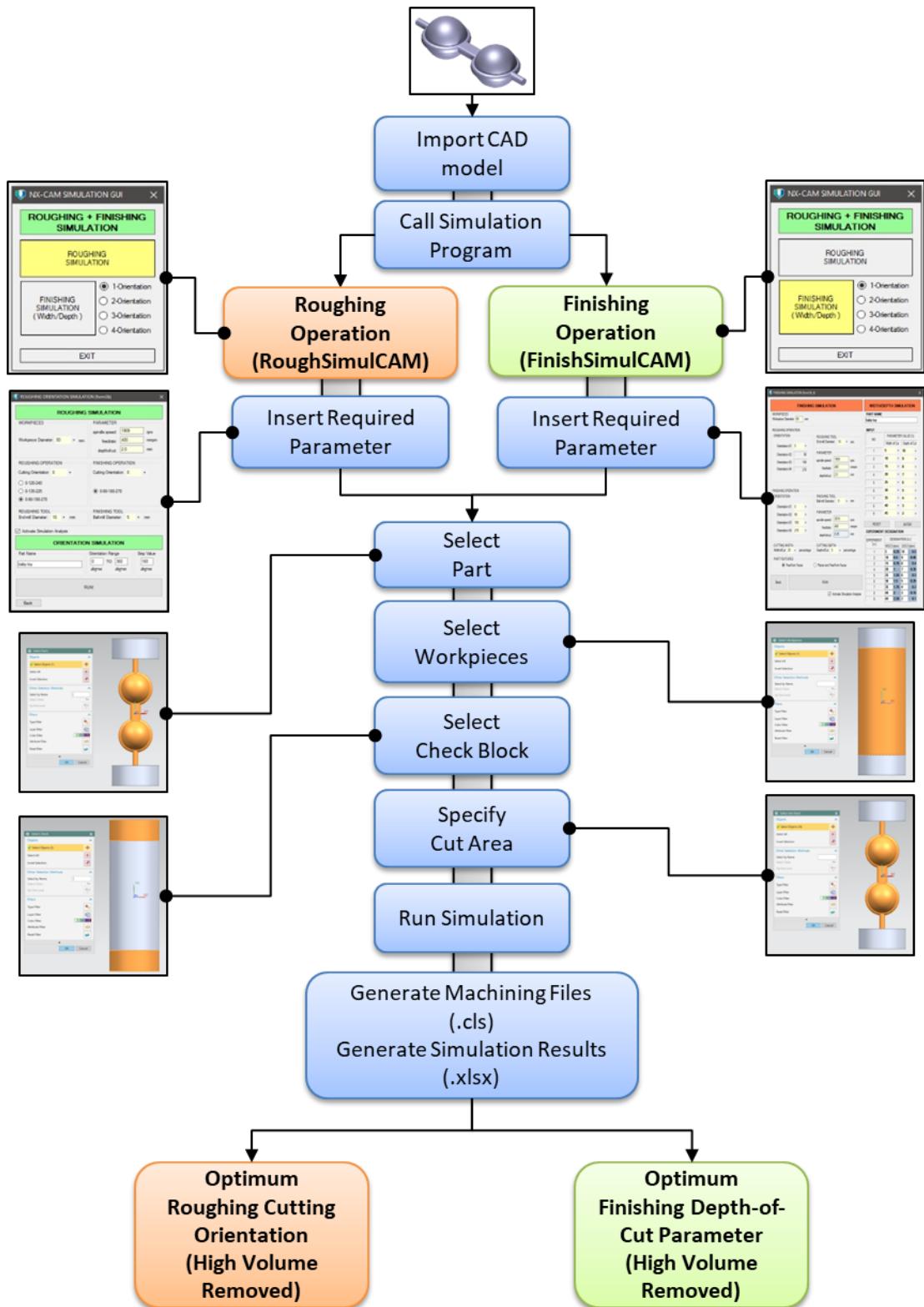


Figure 3.12 RoughSimulCAM and FinishSimulCAM process planning

Overall, there are nine general procedures to execute the machining simulation. Below are further explanations for each procedure:

- 1) **Import CAD Model:** A model initially designed with additional sacrificial support, blank (workpieces), check block and saved in “CATPART” files format.
- 2) **Call Simulation Program:** A developed program is activated by pressing shortcut key (Ctrl+U) in NX 10 software and browse the files from specific directories. Once activated, first GUI windows shows main interface contains a selection for roughing operation (RoughSimulCAM) or finishing operation (FinishSimulCAM). For finishing operation, user is able to select number of finishing orientation, from one to four finishing orientation. The number of orientation were defined based on geometrical features available on machined parts.
- 3) **Insert Required Parameter:** Common parameters required for the simulation program are workpieces diameter, tool diameter (roughing and finishing) and machining parameter (automatically defined based on tools size). In RoughSimulCAM program, another parameter required are cutting angle with different set of orientation and finishing cutting angle with specified orientation. In FinishSimulCAM program, roughing cutting angle is defined based on optimum angle proposed by RoughSimulCAM. Another required parameter was finishing cutting angle, radial depth of cut, axial depth of cut and parts surface selection (freeform or planar surfaces).
- 4) **Select Part:** after completing all the parameters setup, next selection windows will appear to assist the user to define the CAD model to be machined. Initially, the model has been prepared with additional sacrificial support on both end of the parts. The purpose is to ensure the parts can be hold by the sacrificial support to allow the cutting tool machined the parts from several of cutting angle.
- 5) **Select Workpieces and Check Block:** Next selection windows will appear to assist user to define workpieces or blank used in machining simulation. After complete workpieces selection, the next selection windows appear for check

block selection. User need to define the check block at the both end of parts models.

- 6) **Specify Cut Area:** Next procedure is to select the specific cutting area. There is two different approach for each simulation program. For RoughSimulCAM simulation, there are two selections of cut area. First selection defined roughing operation cut area and second selection defined for finishing operation. In FinishSimulCAM simulation, the number of cutting area to be select is depend on the parts features. In freeform faces mode, it is similarly with RoughSimulCAM where first selection is for roughing and second selection is for finishing. In planar and freeform faces mode, there are three cutting area to be defined. First selection is to defined overall cut area for roughing operation, second and third selection is to defined cut area for finishing operation which based on planar faces and freeform faces.
- 7) **Run Simulation:** Once all the parameter is defined, simulation for machining operation is ready to be executed by pressing the RUN button.
- 8) **Generate Machining Files (.cls):** The program will generate machining files (.cls) in parallel with the simulation process. The number of machining files generated are depend on the number of orientation setup. All of these machining files will be saved in specific folder located in desktop directories. Figure 3.13 shows sample of machining files generated from the simulation programs.
- 9) **Generate Simulation Results (.xlsx):** A results will be generated in Excel Files format (.xlsx) once the simulation routines completed. The excel files located in same folder of machining files (.cls) location. Figure 3.14 and Figure 3.15 shows the sample of simulation results in excel files format.

CLS File (73)	CLS File (9)
_babbytoy_20171004_220231_0.cls	_babbytoy_20171004_220231_190.cls
_babbytoy_20171004_220231_5.cls	_babbytoy_20171004_220231_195.cls
_babbytoy_20171004_220231_10.cls	_babbytoy_20171004_220231_200.cls
.	.
_babbytoy_20171004_220231_165.cls	_babbytoy_20171004_220231_355.cls
_babbytoy_20171004_220231_170.cls	_babbytoy_20171004_220231_360.cls
_babbytoy_20171004_220231_175.cls	4_1babbytoy_20171019_092941_5_0.5_.cls
_babbytoy_20171004_220231_180.cls	4_2babbytoy_20171019_092941_10_0.45_.cls
_babbytoy_20171004_220231_185.cls	4_3babbytoy_20171019_092941_15_0.4_.cls

Figure 3.13 Machining files (.clsf) generated from program

Orientation (degree)	Cutting Length (mm)	Cutting Time (min)	Volume Removed (mm³)	Orientation (degree)	Cutting Length (mm)	Cutting Time (min)	Volume Removed (mm³)
5	39,722.02	99.31	171,701.28	185	39,737.23	99.34	171,690.71
10	40,240.29	100.60	171,805.36	190	40,271.35	100.68	171,814.54
15	40,405.64	101.01	172,412.59	195	40,357.17	100.89	172,410.88
20	39,240.57	98.10	171,486.74	200	39,252.02	98.13	171,490.53
25	39,219.65	98.05	171,668.19	205	39,699.74	99.25	171,933.09
30	39,977.55	99.94	171,427.07	210	39,688.89	99.22	171,604.35
35	40,836.74	102.09	172,240.24	215	39,786.23	99.47	172,132.01
40	40,811.11	102.03	171,434.34	220	40,523.47	101.31	172,411.94
45	39,759.66	99.40	172,050.31	225	40,227.46	100.57	172,076.84
50	39,882.51	99.71	171,992.71	230	40,145.61	100.36	172,080.74
55	39,917.77	99.79	171,884.89	235	40,100.93	100.25	171,962.10
60	39,549.12	98.87	171,555.93	240	39,641.13	99.10	171,578.03
65	39,672.15	99.18	171,884.22	245	39,732.02	99.33	172,024.23
70	40,387.82	100.97	171,630.59	250	40,395.15	100.99	171,663.39
75	40,182.59	100.46	172,072.42	255	40,181.46	100.45	172,073.97
80	41,057.81	102.64	172,082.68	260	41,078.51	102.70	172,034.60
85	40,309.78	100.77	171,802.18	265	40,305.76	100.76	171,788.90
90	41,179.51	102.95	172,105.83	270	41,188.43	102.97	172,168.23
95	40,818.41	102.05	172,062.82	275	40,877.71	102.19	172,055.58
100	41,138.84	102.85	172,081.66	280	41,070.50	102.68	172,004.18
105	40,243.03	100.61	172,021.36	285	40,653.29	101.63	172,168.34
110	39,721.43	99.30	171,516.16	290	39,999.67	100.00	171,510.71
115	40,189.59	100.47	171,679.13	295	40,052.04	100.13	171,570.94
120	39,287.03	98.22	171,948.12	300	40,153.12	100.38	171,049.70
125	39,568.92	98.92	172,007.49	305	40,903.73	102.26	172,180.64
130	39,594.28	98.99	171,864.35	310	40,580.28	101.45	172,207.41
135	39,357.18	98.39	171,760.78	315	39,468.22	98.67	171,839.20
140	39,454.28	98.64	171,638.21	320	39,696.21	99.24	171,693.33
145	39,760.39	99.40	171,513.95	325	39,985.42	99.96	171,674.85
150	39,980.53	99.95	171,411.78	330	40,261.95	100.65	171,424.78
155	40,550.43	101.38	171,802.21	335	40,628.89	101.57	171,850.58
160	40,540.47	101.35	171,852.32	340	40,606.03	101.52	171,833.44
165	40,866.57	102.17	172,527.97	345	40,865.60	102.16	172,518.50
170	40,715.93	101.79	171,927.36	350	40,692.91	101.73	171,970.84
175	40,004.23	100.01	171,711.25	355	40,006.73	100.02	171,699.40
180	40,863.27	102.16	172,024.22	360	40,862.20	102.16	171,996.32

Figure 3.14 Simulation results generated from RoughSimulCAM program

Finishing Orientation	Experiment	Cutting Time (min)	Width of Cut (%)		Depth of Cut (%)		Current Stock Volume (mm³)	Original Volume (mm³)	Removed Volume (mm³)
2	experiment 01	514.24	5%	0.25	10%	0.50	8,544.29	201,792.96	193,248.67
2	experiment 02	335.07	10%	0.50	9%	0.45	8,546.46	201,792.96	193,246.50
2	experiment 03	296.44	15%	0.75	8%	0.40	8,548.50	201,792.96	193,244.46
2	experiment 04	270.45	20%	1.00	7%	0.35	8,521.11	201,792.96	193,271.85
2	experiment 05	267.76	25%	1.25	6%	0.30	8,501.71	201,792.96	193,291.25
2	experiment 06	270.87	30%	1.50	5%	0.25	8,480.45	201,792.96	193,312.51
2	experiment 07	290.82	35%	1.75	4%	0.20	8,472.97	201,792.96	193,319.99
2	experiment 08	331.50	40%	2.00	3%	0.15	8,436.31	201,792.96	193,356.65
2	experiment 09	410.19	45%	2.25	2%	0.10	8,454.09	201,792.96	193,338.87

Figure 3.15 Simulation results generated from FinishSimulCAM program

3.4 Machining Experiment

3.4.1 Machining Program Procedure

Series of machining trials are required to verify the developed approaches in terms of machinability, coding stability, process efficiencies and machined parts quality. The machining experiment starts with preparation of models to be machined in CAD format equipped with specific requirement for 4 axis machining (sacrificial support and check block). In the experiment assessment, three different model are selected to be machined. Model selection was made based on size, geometry of the models and surface features. Designed model should be machined-able and within workpieces diameter size. In this research, workpieces size is 50mm diameter then all the selected model was designed to fit workpieces size ratio. The second criteria are geometry of the models. Each selected model possesses different level of geometry to validate the effectiveness of RoughSimulCAM program to provide the best roughing angle for high raw materials remove in roughing machining operations. Last criteria are surface features, which is flat surface and non-flat surface. These criteria were selected to evaluate the effectiveness of FinishSimulCAM program and identify the correlation between different finishing parameter on different machine parts surfaces.

The flow chart in Figure 3.16 explain on the procedure for machining program setup in this experiment, before executing real machining. The procedures start with finding optimum orientation for roughing operation by performing machining simulation with different cutting angle set through RoughSimulCAM application. The orientation set that represent highest volume removed is denoted as optimum orientation for roughing operation. Volume assessment is conducted using Vericut software where the *clf* files generated by RoughSimulCAM application is used as an input. Next procedure is to defined optimum finishing parameter by simulating finishing operation with different depth of cut parameters. FinishSimulCAM application is utilized to execute finishing operation simulation. A set of radial depth-of-cut (RDOC) and axial depth-of-cut (ADOC) is simulated by pairing the potential combination of depth of cut. The parameter set that represent highest volume removed denoted as optimum parameter for finishing operation. After completing roughing and finishing simulation, CL code is generated based on optimum roughing orientation and optimum finishing parameter for final assessment in Vericut software. This assessment

is necessary in order to ensure the machining code to be generated later will run properly without any unexpected problems.

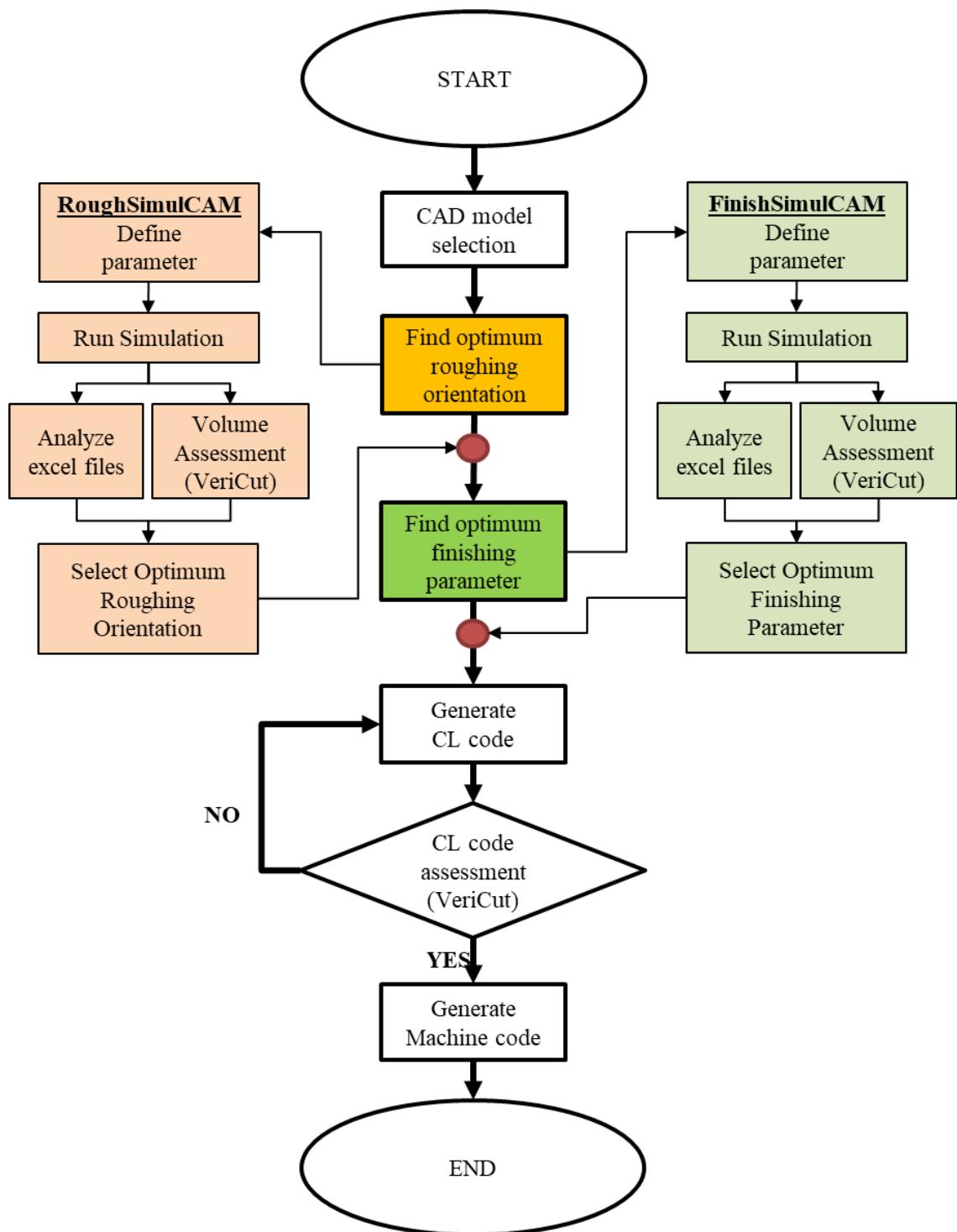


Figure 3.16 Machining program procedure

3.4.2 Machining Setup Procedure

The simulation results from developed program is validated by performing the experimental works. Machining setup are required in order to ensure experiment is executed without any failure. Figure 3.17 shows the overall schematic diagram setup for machining experiment. These setups consist of rotary indexer devices mount on CNC machine working table, cylindrical workpieces (round stock) mount on devices and holder to fix workpieces position during machining. In the beginning, indexing device must be aligned and calibrated accurately on machine working table along X-axis and Y-axis. Next, cylindrical workpiece is mounted on the device and another calibration along X-axis is performed. Additional workpieces holder are required to hold the workpieces firmly during machining. Rotary indexer function used to rotate the workpiece based on the orientation proposed by the simulation programs.

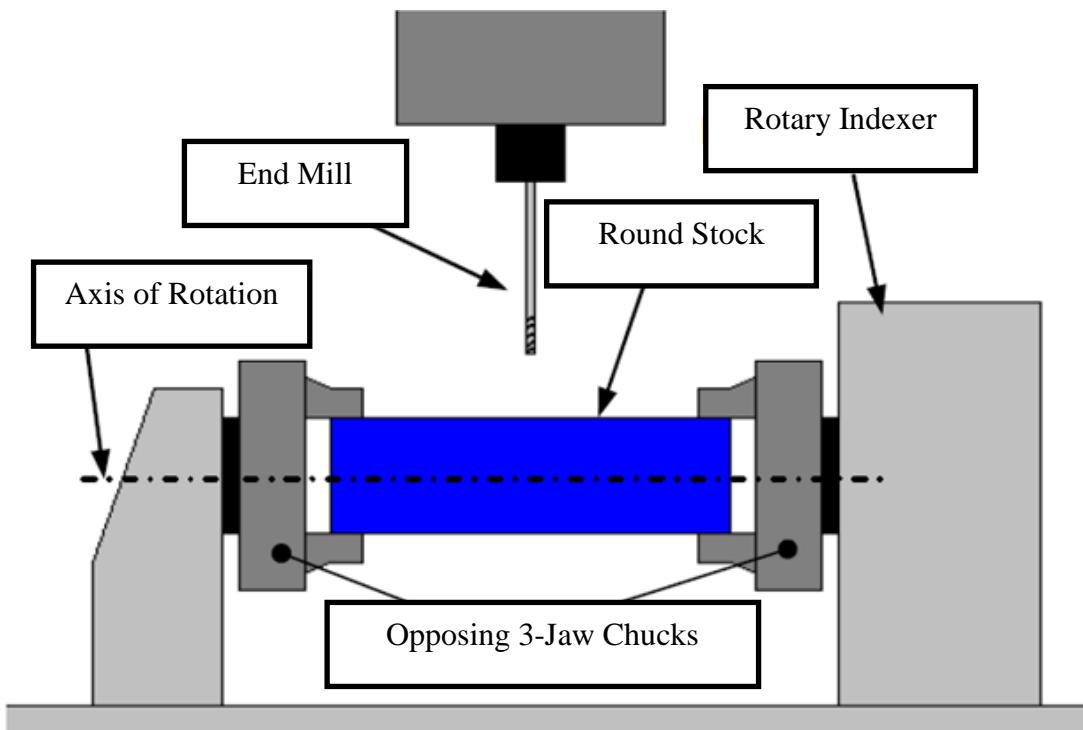


Figure 3.17 Setup procedure for machining operation

3.4.3 Machining Analysis Procedure

Machining results assessment carried out with two different approaches, Volume Removed assessment and Surface Roughness assessment. Volume Removed assessment to validate the accuracy of volume removed between virtual machining simulation results compared to actual machining results. The assessment was carried out based on weight differences. Machined parts are weighted by using weight measurement machine (Figure 3.18) and the value is converted to volume using a formula with the density of aluminium is taken as 0.0027 g/mm³.



Figure 3.18 Weight Measurement Machine

Surface Roughness assessment is conducted to evaluate the relationship of Radial depth of cut (RDOC) and Axial depth of cut (ADOC) cutting parameter towards surface quality. The measurement is carried out by using Surfcom 130A Roughness Tester Machine (Figure 3.19). The measurement is based on average of arithmetic mean average surface roughness (R_a) with 1.0 to 2.0 mm sampling length for each measuring point respectively.



Figure 3.19 Surfcom 130A Roughness Tester Machine

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Simulation Program in 4 Axis Machining

4.1.1 The Simulation Application

There are 3 GUIs that have been developed, named as Main Interface, RoughSimulCAM and FinishSimulCAM. Figure 4.1 shows the application Graphical User Interface (GUI), which is the start-up interface for the user to select the machining operation to be simulated. It was equipped with Roughing Simulation button (RoughSimulCAM) and Finishing Simulation button (FinishSimulCAM) with different selection number of finishing orientation.

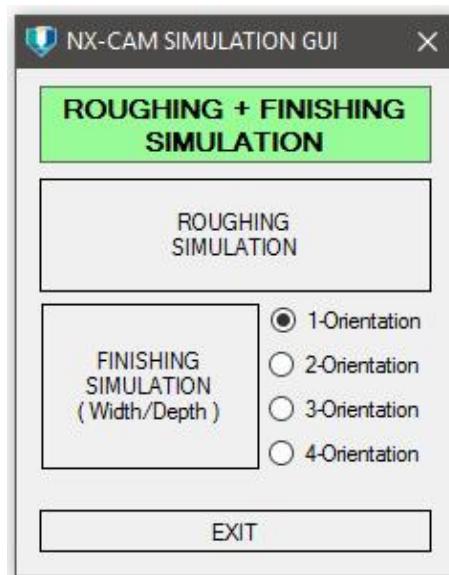


Figure 4.1 Main Interface GUI

In order to execute roughing simulation operation, the user needs to press the 'Roughing Simulation' button then the RoughSimulCAM interface will appear as shown in Figure 4.2. There are a few parameters input required; workpieces diameter, roughing machine parameter (spindle speed, feed rate and depth of cut), cutting

orientation (roughing and finishing), tool diameter (roughing and finishing). The finishing parameters (spindle speed, feed rate and depth of cut) was are already built-in inside the program and will automatically decide based on finishing tool size. All the required parameter in the RoughSimulCAM GUI need to be entered by the user before pressing the 'Run' button to start the simulation process. In order to perform continuous roughing simulation analysis, user need to activate the 'Simulation Analysis' tick box, above the Orientation Simulation box. Once activated, simulation analyses are ready to be executed based on information defined by the user.

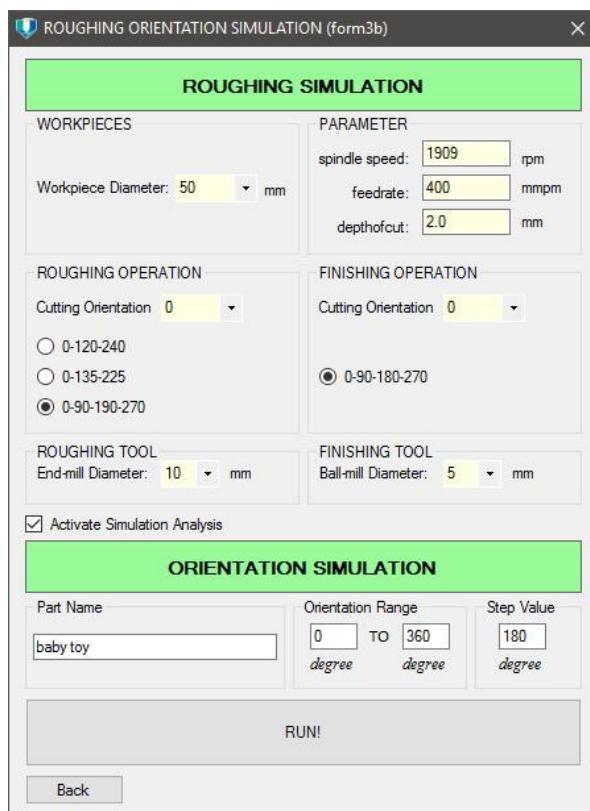


Figure 4.2 RoughSimulCAM GUI

Figure 4.3 shows the GUI for finishing simulation operation, name as FinishSimulCAM. In this application, cutting orientations for roughing are defined based on optimum cutting orientation proposed by RoughSimulCAM application, as well as machining parameter (spindle speed, feed rate and depth of cut) and roughing tool size. For finishing operation, number of orientation are defined based on parts geometry and features. Other machining parameters such as spindle speed and feed rate will be decided by the application based on tool diameter input. FinishSimulCAM

application offer a different simulation approach, where user is able to simulate and manipulate different depth of cut parameter, consist of cutting width or Radial depth of cut (RDOC) and cutting depth or Axial depth of cut (ADOC). The purpose of the parameter manipulation is to simulate and identify the correlation between these two parameter on the total volume removed and finishing surface quality. In addition, FinishSimulCAM application also equipped with function to execute finishing operation with multiple finishing cutting tool integration based on geometrical features that available on the machined parts (Nafis, Case, & Watts, 2015). The function can be selected in part features categories, consist of “Freeform Faces” to use Ball-Mill tool only and “Planar and Free-Form Faces” for integrating Flat End-Mill tool with Ball-Mill tool. In order to activate continuous simulation analysis, user need to tick the ‘Simulation Analysis’ box below the Run button. Once activated, simulation analysis is ready to be executed and continuously repeating the experiment based on input defined by the user.

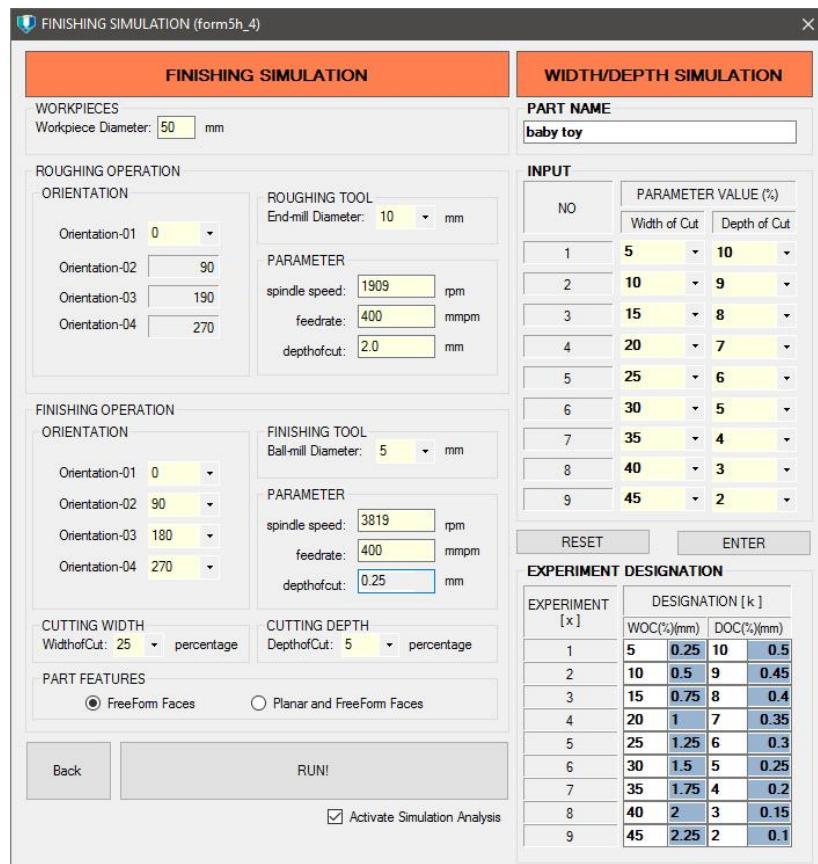


Figure 4.3 FinishSimulCAM GUI

4.1.2 Simulation Application Performances

In order to illustrate the overview of simulation operation, the differences in process planning steps between conventional and proposed approaches can be seen in Figure 4.4. Conventional approach is manual methods that are typically used to build machining programs and requires a significant user intervention and efforts to execute the repetitive processes (Turley et al., 2014). Some parameters and settings for each operation need to be changed in order to run the simulations with several constant parameters. In this study, certain level of automation is expected to be embedded in the operation build-up routines. The proposed approach is an improvised method by developing a custom application to build a machining program in NX with the addition of several automation elements.

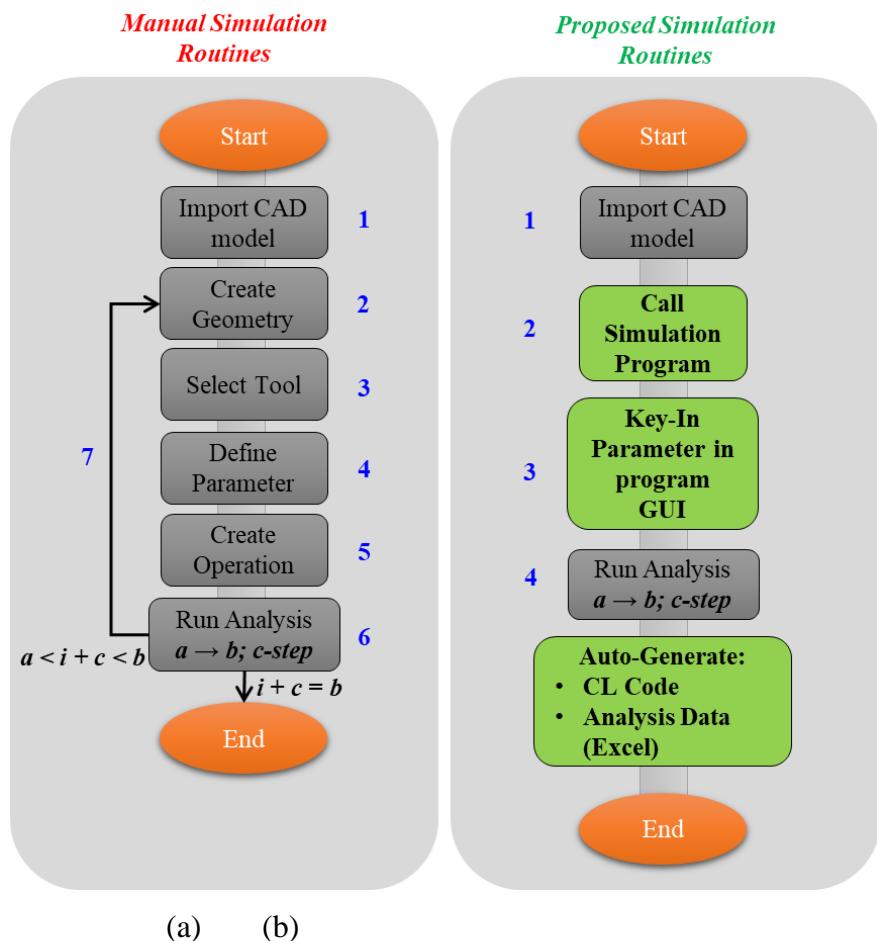


Figure 4.4 Comparison of simulation approach

The simulation will run continuously without requiring user intervention between the part geometry in 4 axis machining operation. Consequently, if there are many parts geometry involved in one operation, the application will automatically loop the simulation to the next operation efficiently. Journaling program codes are recorded through the tool in NX CAM starts from “Create Geometry” (level-2) to “Create Operation” (level-5). Some parameters values that need to be set in each level have been simplified and grouped in GUI program window. Through this method, the proposed approach has managed to reduce the processing step from 6 steps to just 3 steps only.

4.1.3 Comparison of Manual and Proposed Simulation Approach

A few machining simulation test have been performed in NX-CAM system in order to compare the effectiveness of proposed approach with the conventional approach. The simulation was performed by a machinist with experience in using NX-CAM system. The details process of constructing the machining operation are shown in Table 4.1 by using RoughSimulCAM program. Baby Toy was used as a model references to evaluate the effectiveness of both approaches. Referring to the table, manual simulation approach processing time is taken based on the totally human intervention to build the machining programmes or CLSF code. The timing measured start from imports CAD model operation and stopped once the CAM system generate CLSF code output. Specific time for each operations was defined accordingly based on effort required for each. Meanwhile, proposed simulation approach was measured based on time differences between program start and end. The total of time consumed is then divided by 73 to get the amount of time required to produce a machining program. The result of simulation presented in graph in order to visualize the gap between two different approaches. Referring to Figure 4.5, that the proposed approach are managed to improve the overall processing time up to 77.3%. In terms of total time, manual approach requires 22.50 min to develop machining operation of four roughing orientation and two finishing orientation. Proposed approach with the same orientation set only required 5.11 min to construct the machining operations for one CLSF code.

Table 4.1 Comparison of manual and proposed simulation approach

Model References: Babytoy_20171004_220231		
RoughSimulCAM	Program Start:	10:02:31 PM
Program Information	Program End:	11:53:52 PM
	Time Consumed:	1:51:21
	Total Program Run Time (min):	111
	Cutting Angle Interval (degree):	5
	Total CL code produced (unit):	73
Operation	Manual Simulation Approach (min)	Proposed Simulation Approach (min)
Imports CAD model	1.00	1.00
Run SimulCAM Program		0.50
Key-In Parameter	-	2.00
Start SimulCAM Analysis		0.08
Create Tool (Roughing)	0.50	0.04
Create Geometry_0°	0.50	0.04
Create Operation-1_roughing	1.00	0.07
Define Parameter-1_roughing	1.50	0.11
Create Geometry_90°	0.50	0.04
Create Operation-2_roughing	1.00	0.07
Define Parameter-2_roughing	1.50	0.11
Create Geometry_190°	0.50	0.04
Create Operation-3_roughing	1.00	0.07
Define Parameter-3_roughing	1.50	0.11
Create Geometry_270°	0.50	0.04
Create Operation-4_roughing	1.00	0.07
Define Parameter-4_roughing	1.50	0.11
Create Tool (Finishing)	0.50	0.04
Create Geometry_0°	0.50	0.04
Create Operation-5_finishing	1.00	0.07
Define Parameter-5_finishing	1.50	0.11
Create Geometry_180°	0.50	0.04
Create Operation-6_finishing	1.00	0.07
Define Parameter-6_finishing	1.50	0.11
Generate Toolpath	2.00	0.14
Output CLSF Code	0.50	0.04
Total Time (min):	22.50	5.11
Diff.:	-77.3%	

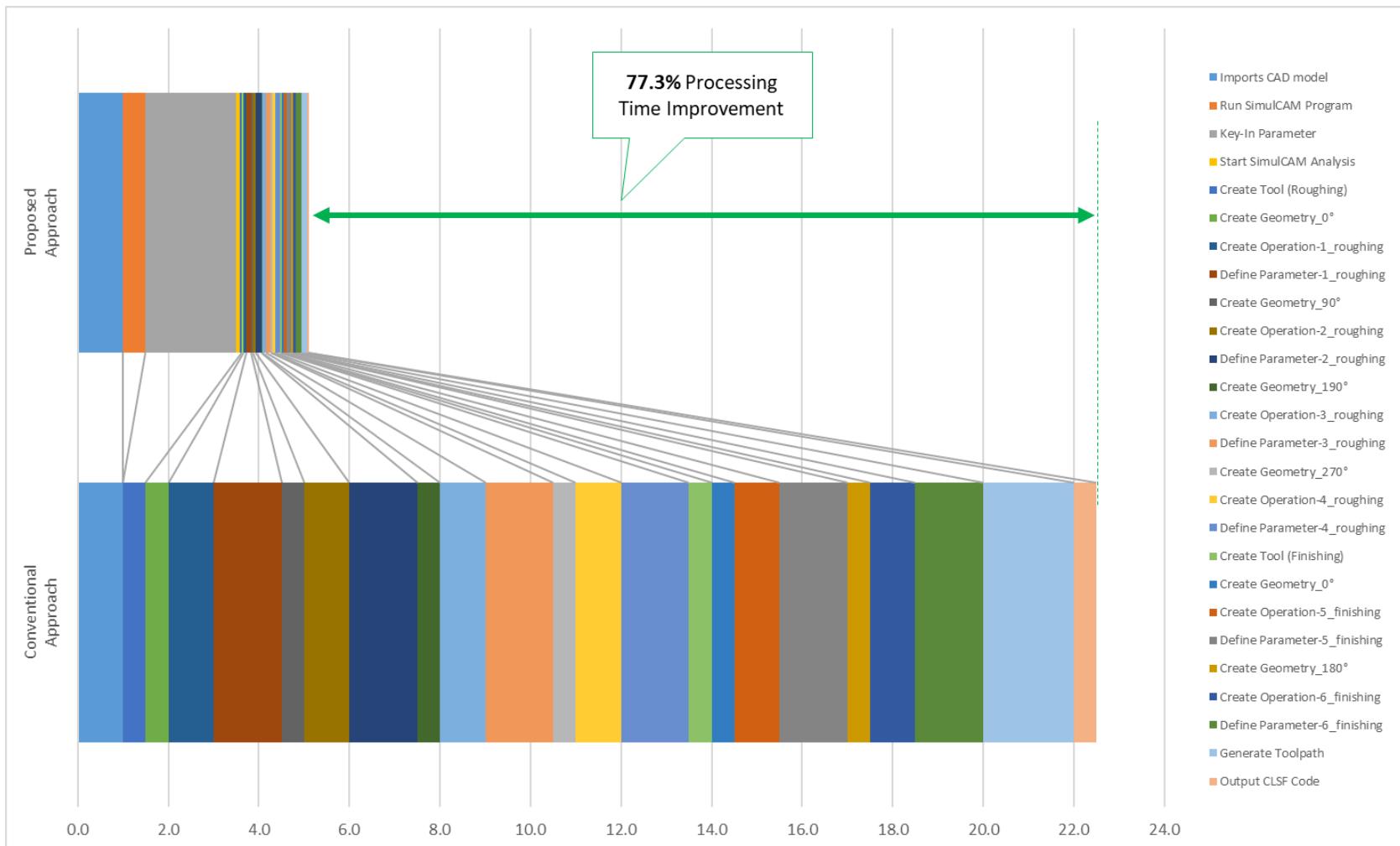


Figure 4.5 Conventional and proposed approach comparison in graph data

4.2 Machining Simulation

4.2.1 Roughing Simulation Outcomes

A few of models with different geometrical and shape were used to validate the developed RoughSimulCAM and FinishSimulCAM applications. For roughing operation, RoughSimulCAM application are used to identify an optimum roughing orientation set. Table 4.2 shows the results of the simulation analysis for roughing operations, including set of orientation, initial cutting angle, volume removed and roughing percentages. From the table, Initial Cutting Angle indicated the first angle value based on different orientation set approach. In roughing operation, three different set of orientations are utilized to execute the simulation analysis based RoughSimulCAM application, (0° - 120° - 240°), (0° - 135° - 225°) and (0° - 90° - 190° - 270°). Volume Removed Roughing represents total material removed in roughing operation and Volume Removed Finishing indicates the total material removed in finishing operation. The value of volume removed is measured by using Vericut software. Roughing percentage is calculated based on the volume removed in roughing operation compared to total volume removed for the overall machining operation. Based on the results presented in the table, it shows that the RoughSimulCAM application successfully run the machining simulation for a few parts model with different geometry and surfaces features. This results conclude that RoughSimulCAM application capable to identify and propose the best cutting angle with high volume removed for roughing operation.

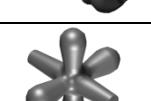
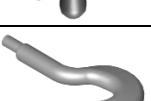
Table 4.2 Highest volume removed results generated by RoughSimulCAM

Model	Orientation Set (°)	Initial	Volume	Volume	Roughing Percentage (%)
		Cutting Angle (°)	Removed Roughing (mm ³)	Removed Finishing (mm ³)	
Baby Toy	0-120-240	155°	168,888.45	18,360.76	90.19%
	0-135-225	100°	168,470.44	18,581.87	90.07%
	0-90-190-270	165°	172,530.24	14,816.48	92.09%
Lego Block	0-120-240	300°	146,978.76	15,328.77	90.56%
	0-135-225	315°	147,848.89	14,482.15	91.08%
	0-90-190-270	90°	149,660.64	12,677.93	92.19%
Fan Blade	0-120-240	250°	67,676.94	5,331.19	92.70%
	0-135-225	25°	67,596.11	5,297.66	92.73%
	0-90-190-270	225°	68,501.70	4,602.23	93.70%
Metal Hook	0-120-240	300°	181,258.07	11,765.96	93.90%
	0-135-225	180°	181,407.15	11,816.69	93.88%
	0-90-190-270	90°	185,986.61	7,280.86	96.23%
Worm Gear	0-120-240	155°	83,540.09	36,725.97	69.46%
	0-135-225	340°	84,001.73	36,252.98	69.85%
	0-90-190-270	315°	87,764.52	32,485.67	72.98%
Alphabet S	0-120-240	270°	155,671.35	9,330.49	94.35%
	0-135-225	310°	155,405.28	9,583.52	94.19%
	0-90-190-270	90°	158,509.70	6,612.02	96.00%
Piston Component	0-120-240	205°	249,056.55	24,163.61	91.16%
	0-135-225	20°	249,049.50	23,992.72	91.21%
	0-90-190-270	270°	256,037.09	17,672.14	93.54%
Salt Bottle	0-120-240	300°	104,061.70	16,615.41	86.23%
	0-135-225	225°	104,720.27	15,959.92	86.78%
	0-90-190-270	270°	107,434.00	13,297.75	88.99%
Toy Jack	0-120-240	5°	85,031.52	5,951.51	93.46%
	0-135-225	140°	84,810.12	6,135.00	93.25%
	0-90-190-270	285°	86,818.04	4,447.90	95.13%
Crane Hook	0-120-240	170°	168,761.72	8,499.99	95.20%
	0-135-225	45°	166,978.63	10,432.05	94.12%
	0-90-190-270	90°	171,834.74	5,698.09	96.79%

4.2.1 Finishing Simulation Outcomes

In finishing operation, the machining simulations were executed through FinishSimulCAM application. This application is purposely developed to demonstrate the correlation of Radial depth-of-cut (RDOC) and axial depth-of-cut (ADOC) and propose an optimum combination percentage. The evaluation criterion for the simulation is based on the total volume removed and excess volume left on the workpiece. Table 4.3 summarize the results for the finishing simulation application. The results were classified into three categories, which are minimum volume removed, median volume removed and maximum volume removed. The purpose of this categorisation is to visualize the implications of each category towards surface roughness in experimental machining operation that will be discussed in the next section. The percentage column indicates the value of depth of cut parameter (RDOC & ADOC) that has been proposed by the application. Volume removed represents the total volume removed including roughing and finishing operation. Referring to the results for each model, it shown that the combination of higher RDOC with lower ADOC indicate the highest volume removed compared to lower RDOC and higher ADOC. Hence, the combination of higher RDOC values with lower ADOC in machining operations will further increase the quantity of volume removed for the machined parts. Based on the results presented in the table, it shows that the FinishSimulCAM application successfully run the machining simulation for a few parts model with different geometry and surfaces features. This results conclude that FinishSimulCAM application capable to identify and propose the best combination of Radial Depth of Cut (RDOC) and Axial Depth of Cut (ADOC) with high volume removed for finishing operation.

Table 4.3 Highest volume removed results generated by FinishSimulCAM

Model	Classification	Percentage (%)		Millimetre Cube (mm³)	
		RDOC	ADOC	Volume Removed	Excess Volume
		Min	Max		
Baby Toy		Min	5	152,689.36	306.04
		Med	25	152,932.29	99.44
		Max	45	153,059.45	64.69
Lego Block		Min	15	165,811.45	412.19
		Med	30	166,144.13	177.74
		Max	40	166,218.16	125.17
Fan Blade		Min	30	73,041.12	646.99
		Med	5	73,643.32	84.04
		Max	35	73,660.32	73.55
Metal Hook		Min	5	193,098.82	1,328.43
		Med	10	193,347.95	1,110.00
		Max	45	193,474.98	1,061.25
Worm Gear		Min	10	121,035.06	912.60
		Med	30	121,125.89	783.13
		Max	35	121,195.93	775.73
Alphabet S		Min	5	165,099.77	301.31
		Med	25	165,300.04	149.55
		Max	40	165,426.69	81.24
Piston Component		Min	10	275,294.64	852.66
		Med	25	275,505.38	638.91
		Max	40	275,667.41	516.43
Salt Bottle		Min	15	121,182.56	104.95
		Med	35	121,271.52	82.95
		Max	40	121,307.80	63.77
Toy Jack		Min	15	91,728.61	94.08
		Med	30	91,743.01	90.63
		Max	40	91,755.35	88.70
Crane Hook		Min	5	177,621.18	254.74
		Med	25	177,728.45	164.54
		Max	45	177,830.93	112.37

4.3 Machining Experiment

4.3.1 Machined Model Assessment

This section will discuss in detail about the machining assessment for selected CAD model. The main purpose is to validate the functionality and effectiveness of the developed application (RoughSimulCAM and FinishSimulCAM). The experiment started with selecting the model from previous simulation analysis and perform a detail assessment. Three model are selected which include Alphabet S, Baby Toy and Toy Jack. The selected models contained various geometrical and surfaces features, which is useful to evaluate the machining experiment outcome. The experiment executed based on three different machining criteria for each models, which are based on minimum, median and maximum volume removed.

Table 4.4 shows the detail simulation assessment results of three experiments using Alphabet S model. End mill tool with 10mm diameter size was used to execute roughing operation. Based on simulation, the optimum cutting orientation proposed by RoughSimulCAM application is 90° - 180° - 280° - 0° . The machining time recorded for roughing operation is 86.00 minutes. All parameter within roughing operation remain the same for all experiment due to similar optimum cutting orientation were used. The assessment then proceeded to finishing operation through FinishSimulCAM application. Alphabet S model consist of two different surfaces, which is flat and non-flat surface. Therefore, finishing operation need to be executed with multiple cutting tools by using End mill and Ball mill tools with diameter 6mm. These function already built-in in FinishSimulCAM where it has a selection button in user interfaces. Based on visual assessment, the feasible finishing orientation for Alphabet S model is 0° and 180° , where these two angles have large surface coverage to remove material efficiently. Machining time in finishing operation is different due to each experiment employed different cutting parameter (RDOC and ADOC). Experiment 1 executed with 5% RDOC and 10% ADOC parameter, Experiment 2 with 25% RDOC and 6% ADOC parameter and Experiment 3 with 40% ADOC and 3% RDOC parameter.

Based on simulation, experiment 3 indicates a bit higher machining time rather than experiment 2 and lower than experiment 1. In terms of excess volume, experiment

3 indicates minimum amount of remaining volume compared to experiment 1 and experiment 2.

Table 4.5 shows the detail machining simulation assessment results using Baby Toy model. Three experiment was executed with same roughing parameter and different finishing parameter. In roughing operation, 10mm end mill tool diameter was used to execute roughing machining. Based on machining simulation, the optimum cutting orientation proposed by RoughSimulCAM application is 165° - 255° - 355° - 75° . The machining time recorded for roughing operation is 81.40 minutes. All parameter within roughing operation remain same for all experiment due to similar optimum cutting orientation were used. The assessment then proceeded to finishing operation through FinishSimulCAM application. Baby Toy model consist of two different surfaces features, which is flat surface and non-flat surface. Same as Alphabet S model, finishing operation executed with multiple cutting tools method by using 6mm End mill tool diameter and 6mm Ball mills tool diameter. Based on visual assessment, the feasible finishing orientation for Baby Toy model is 0° and 180° , where these two angles have large surface coverage to remove material efficiently. Experiment 1 executed with 5% RDOC and 10% ADOC parameter, Experiment 2 with 25% RDOC and 6% ADOC parameter and Experiment 3 with 45% ADOC and 2% RDOC parameter. Based on simulation, experiment 1 indicates higher machining time, which is 378 minutes, followed by experiment 3 with 344 minutes and experiment 2 with lowest machining time, 167 minutes. In terms of excess volume calculated using VERICUT software, experiment 3 indicates minimum amount of excess volume with 65mm^3 , followed by experiment 2 with 99mm^3 and experiment 1 with 306 mm^3 .

Table 4.6 shows the detail simulation assessment results for Toy Jack model. Three experiment was executed with same roughing parameter and different finishing parameter. In roughing operation, 10mm end mill tool diameter was used to execute roughing machining. Based on machining simulation, the optimum cutting orientation proposed by RoughSimulCAM application for this model is 285° - 15° - 115° - 195° . The machining time recorded for roughing operation is 51.92 minutes. All parameter within roughing operation remain same for all experiment due to similar optimum cutting orientation were used. The assessment then proceeded to finishing operation through FinishSimulCAM application. Toy Jack model is different from previous two model, where this model only contained non-flat surface. Therefore, finishing operation was executed with single cutting operation using 6mm Ball mill tool diameter. Based on visual assessment, the feasible finishing orientation for Toy Jack model is 45° - 135° - 225° - 315° , where these angles have open surface area for maximum depth of cutting tool. Experiment 1 executed with 15% RDOC and 8% ADOC parameter, Experiment 2 with 30% RDOC and 5% ADOC parameter and Experiment 3 with 40% ADOC and 3% RDOC parameter. Based on simulation, experiment 3 indicates higher machining time, which is 212 minutes, followed by experiment 1 with 160 minutes and experiment 2 with lowest machining time, 150 minutes. In terms of excess volume calculated using VERICUT software, experiment 3 indicates minimum amount of excess volume with 89mm^3 , followed by experiment 2 with 91mm^3 and experiment 1 with 94 mm^3 .

Table 4.4 Machining simulation results: Alphabet S

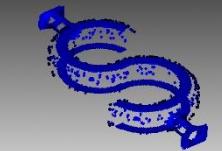
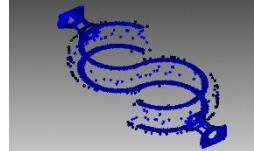
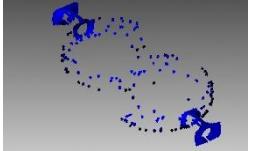
Model		Alphabet S			
					
Classification		Minimum Volume Removed	Median Volume Removed	Maximum Volume Removed	
		Experiment 1	Experiment 2	Experiment 3	
Roughing Operation	Tool Diameter	mm	End Mill : 10		
	Cutting Orientation	°	90° - 180° - 280° - 0°		
	Machining Time	min	86.00		
Finishing Operation	Tool Diameter	mm	End Mill : 6mm Ball Mill : 6mm		
	Cutting Orientation	°	0° - 180°		
	Radial DOC	%	5	25	40
	Axial DOC		10	6	3
	Machining Time	min	294	182	237
Volume Assessment	Original Volume	mm³	178,678		
	Stock Volume		12,823	12,623	12,496
	Removed Volume		165,100	165,300	165,427
	Excess Volume		301	150	81
Excess Volume Simulation (VeriCut)					

Table 4.5 Machining simulation results: Baby Toy

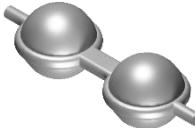
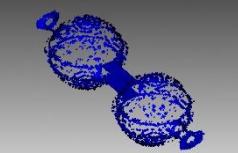
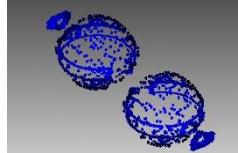
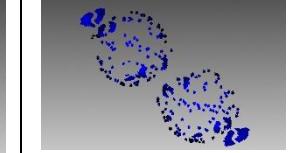
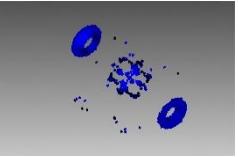
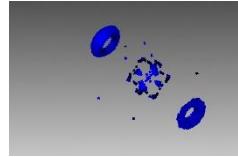
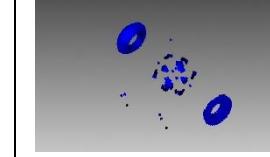
Model			Baby Toy		
					
Classification			Minimum Volume Removed	Median Volume Removed	Maximum Volume Removed
			Experiment 1	Experiment 2	Experiment 3
Roughing Operation	Tool Diameter	mm	End Mill : 10mm		
	Cutting Orientation	°	165° - 255° - 355° - 75°		
	Machining Time	min	81.40		
Finishing Operation	Tool Diameter	mm	End Mill : 6mm Ball Mill : 6mm		
	Cutting Orientation	°	0° - 180°		
	Radial DOC	%	5	25	45
	Axial DOC	%	10	6	2
	Machining Time	min	378	167	344
Volume Assessment	Original Volume	mm ³	175,442		
	Stock Volume		22,035	21,792	21,665
	Removed Volume		152,689	152,932	153,059
	Excess Volume		306	99	65
Excess Volume Simulation (VeriCut)					

Table 4.6 Machining simulation results: Toy Jack

Model		Toy Jack		
				
Classification		Minimum Volume Removed	Median Volume Removed	Maximum Volume Removed
		Experiment 1	Experiment 2	Experiment 3
Roughing Operation	Tool Diameter	mm	End Mill : 10mm	
	Cutting Orientation	°	285° - 15° - 115° - 195°	
	Machining Time	min	51.92	
Finishing Operation	Tool Diameter	mm	End Mill : 6mm Ball Mill : 6mm	
	Cutting Orientation	°	45°-135°-225°-315°	
	Radial DOC	%	15	30
	Axial DOC		8	5
	Machining Time	min	160	150
Volume Assessment	Original Volume	mm³	97,765	
	Stock Volume		6,036	6,022
	Removed Volume		91,729	91,743
	Excess Volume		94	91
Excess Volume Simulation (VeriCut)				

4.3.2 Volume Removed Assessment

This section will discuss about volume removed assessment for the selected machined model. The assessment is required in order to measure the accuracy of simulation machining results compared to actual machining results. The machined parts are weighted and the value is converted to volume using a formula with the density of aluminium is taken as 0.0027 g/mm^3 . Figure 4.6 shows the volume removed assessment results for Alphabet S model. The deviation range is about 0.08% (minimum) to 0.50% (maximum), with average 0.29%. Figure 4.7 shows the assessment results for Baby Toy model. The deviation range is about 0.49% (minimum) to 0.69% (maximum), with average 0.59%. Figure 4.8 shows the assessment results for Toy Jack model. The deviation range is about 0.12% (minimum) to 0.57% (maximum), with average 0.34%. In overall, average deviation among the simulation and actual machining is around 0.70%. The volume removed in actual machining can be larger or smaller than simulation volume removed due to some dynamic machine error during workpiece setup at the beginning of the actual machining. However, this machining error was not occurring during virtual machining simulation as all the setup was solely perfect in the software interface and not require any physical setup to perform the machining simulation operation.

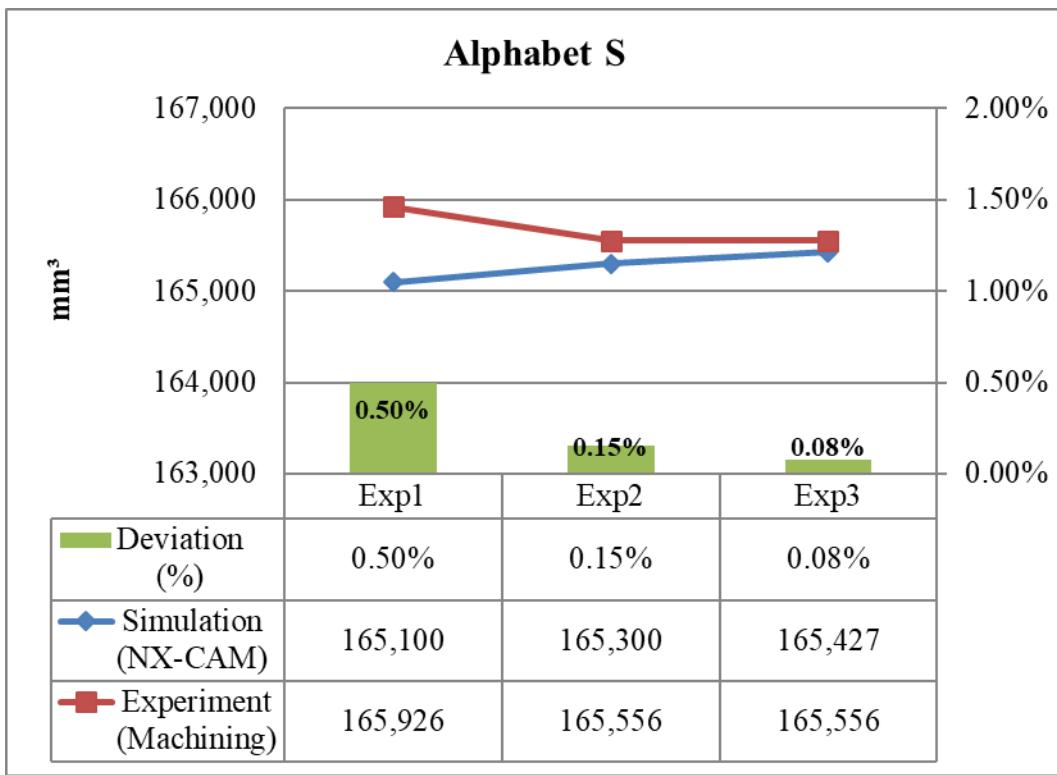


Figure 4.6 Volume removed assessment for Alphabet S model

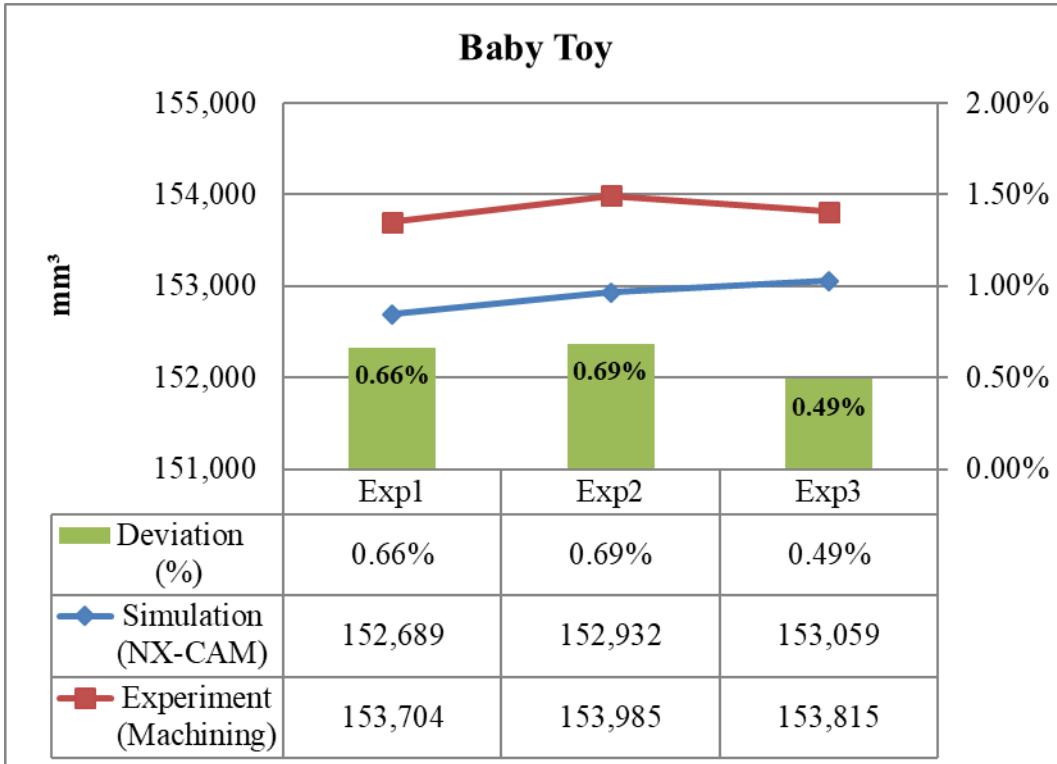


Figure 4.7 Volume removed assessment for Baby Toy model

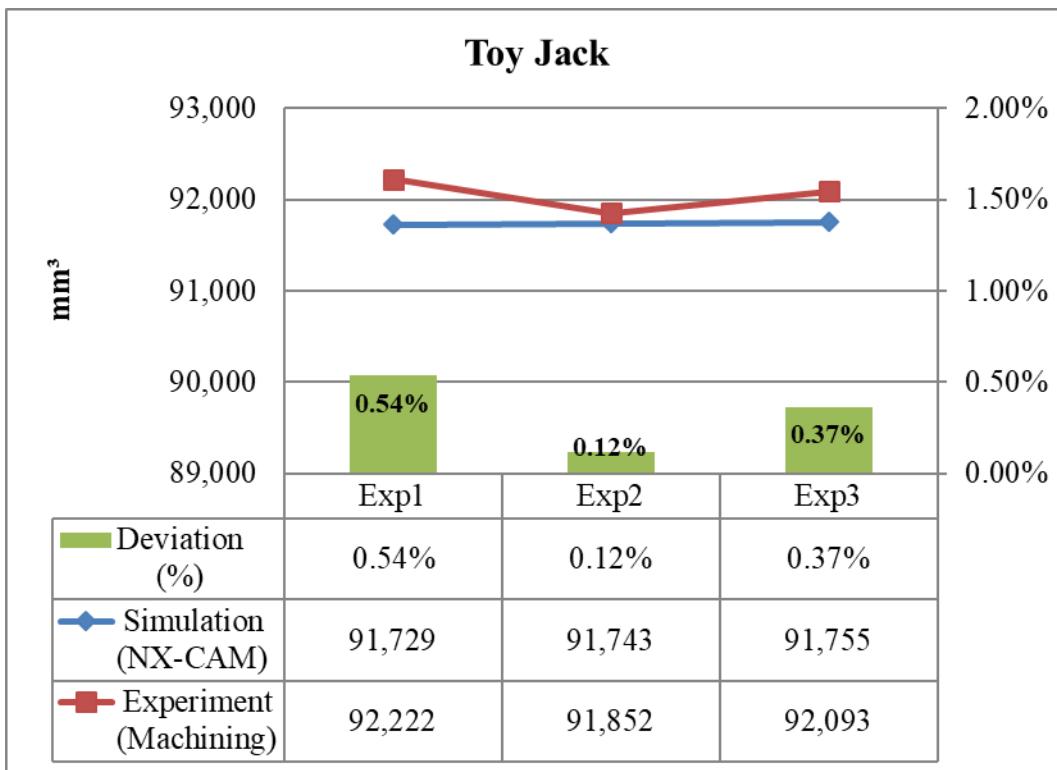


Figure 4.8 Volume removed assessment for Toy Jack model

4.3.3 Surface Roughness Assessment

This section will discuss about surface roughness assessment for the selected machined model. In this study, the roughness assessment is conducted to evaluate the relationship of Radial depth of cut (RDOC) and Axial depth of cut (ADOC) cutting parameter towards surface quality. The measurement is carried out by using Surfcom 130A Roughness Tester Machine, based on average of arithmetic mean average surface roughness (R_a) with 1.0 to 2.0 mm sampling length for each measuring point respectively.

Figure 4.9 shows the results of surface roughness assessment for Alphabet S model. In overall 9 location point was measured from two sides surface, 5 points was taken from flat surfaces and 4 points from non-flat surfaces. During finishing operations, side A is the first orientation while side B is the second orientation. In general, there is a significant difference in the value of roughness between flat surface and non-flat surface. This is due to the difference type of end mill used to cater the flat and non-flat surfaces. This approach is implemented based on the previous study that suggest the multiple tool integration in the finishing operation to improve surface quality. (Nafis et al., 2015). Table 4.7 shows the surface roughness results trends in the three experiment. The flat surface (F) point in all three experiment shows roughness value lower than $0.4\mu\text{m}$ on both sides of the model. However, for non-flat (NF) surface, experiment 1 shows high roughness value for all NF point on side A surface and low roughness value for all NF point on side B surface. Experiment 2 shows high roughness value for all NF point on side A and 2 NF point on side B (NF1 and NF3). Experiment 3 shows roughness value lower than $1.0\mu\text{m}$ for all NF point except point NF1 on side B.

Figure 4.10 shows the surface roughness results for Baby Toy model. 7 location point was measured from two side surface, where 3 points was taken for flat surfaces and 4 points for non-flat surfaces as shown in Table 4.8. In overall, all measured point shows roughness value lower than $1.0\mu\text{m}$. Experiment 1 shows high roughness value on non-flat (NF) surfaces compared to flat (F) surfaces for both machining side, where $0.93\mu\text{m}$ at point NF1 on side A and point NF4 on side B. Experiment 2 shows high roughness value at point NF4 on side A ($0.82\mu\text{m}$) and at point NF4 on side B ($0.94\mu\text{m}$). Meanwhile experiment 3 shows high roughness value, which is $0.74\mu\text{m}$ at point NF2 on side A and at point NF1 on side B.

Figure 4.11 shows the result of surface roughness for Toy Jack model. Roughness measurement point for this model is divided into four sides with two point on each side, in total consist 8 roughness point. This model only has non-flat surfaces (NF), therefore all roughness values are measured on the same features. In average, all experiment shows roughness value below 1.0 μm where, experiment 1 achieved 0.88 μm , experiment 2 achieved 0.76 μm and experiment 3 achieved 0.71 μm .

According to Baptista (2000), there is three level of finishing based on roughness values which are 0.5 μm , 1.0 μm and 1.8 μm (Baptista & Antune Simões, 2000). Roughness values around 0.5 μm indicates as roughness equivalent to manual polish, 1.0 μm indicates as an acceptable roughness and 1.8 μm is still acceptable but requires manual polishing. Therefore, the surface roughness measured for all three machined parts are within the acceptable standard limit of roughness produced by milling machines. The actual machining results also indicate the practicality of the FinishSimulCAM application which proven to produce the part quality within acceptable roughness, as overall roughness value in actual machining operation achieved at 1.0 μm to 1.4 μm in average.

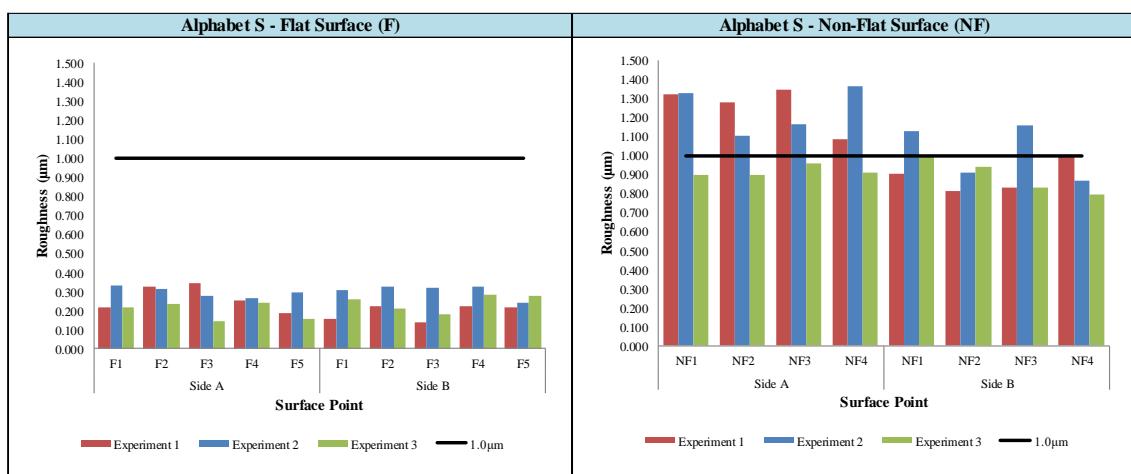


Figure 4.9 Surface roughness assesment results: Alphabet S

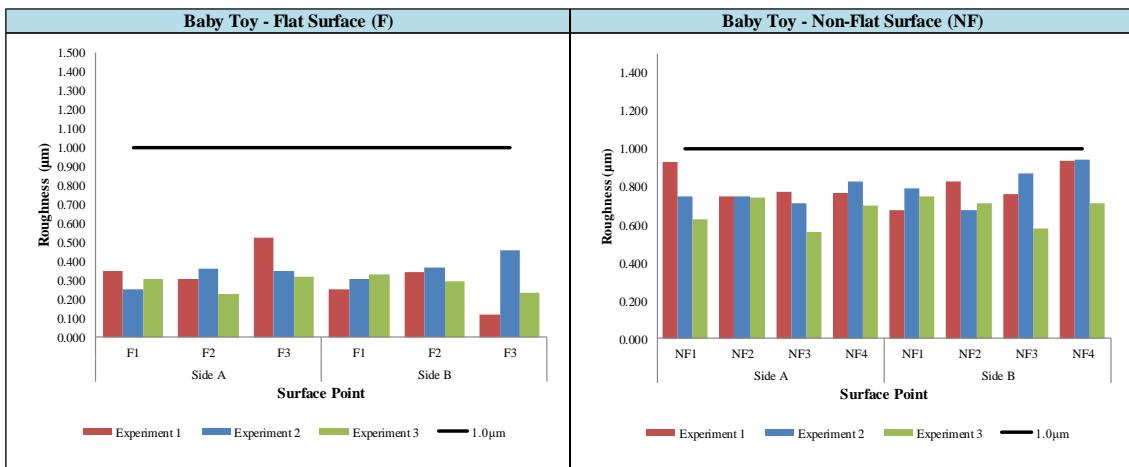


Figure 4.10 Surface roughness assessment results: Baby Toy

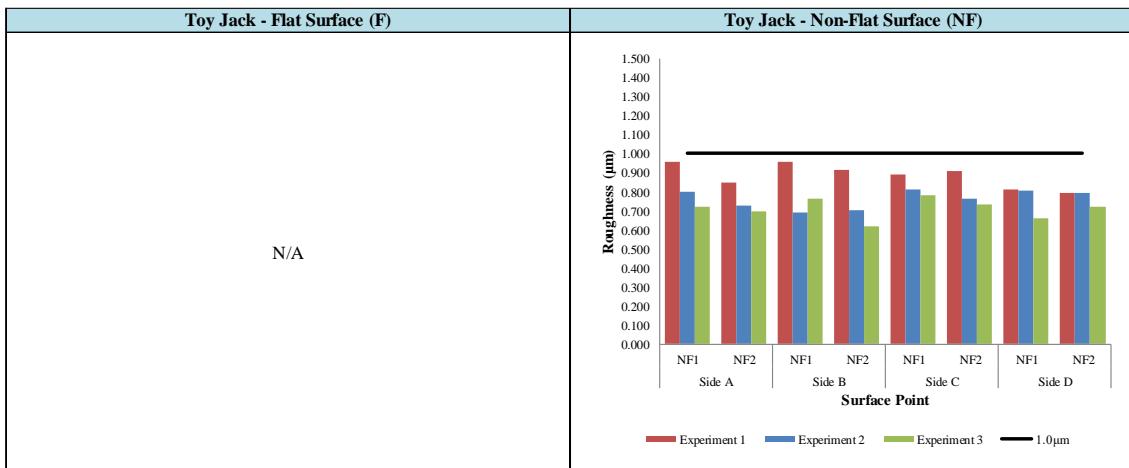
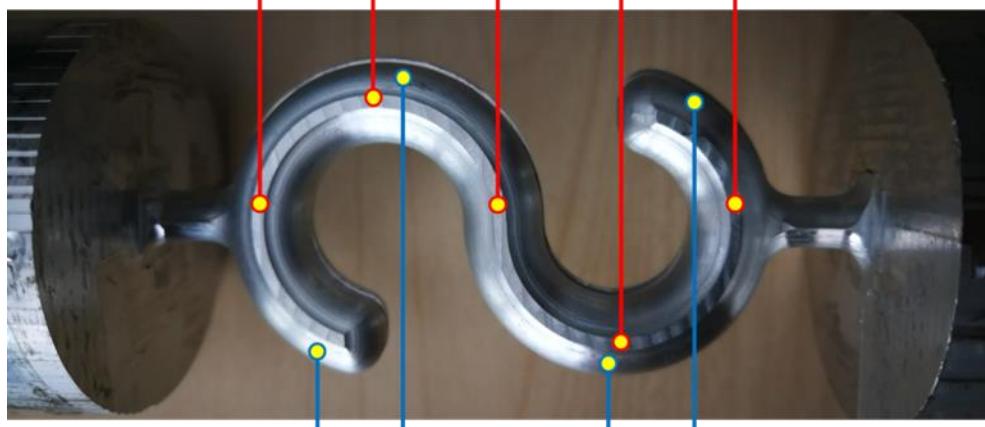


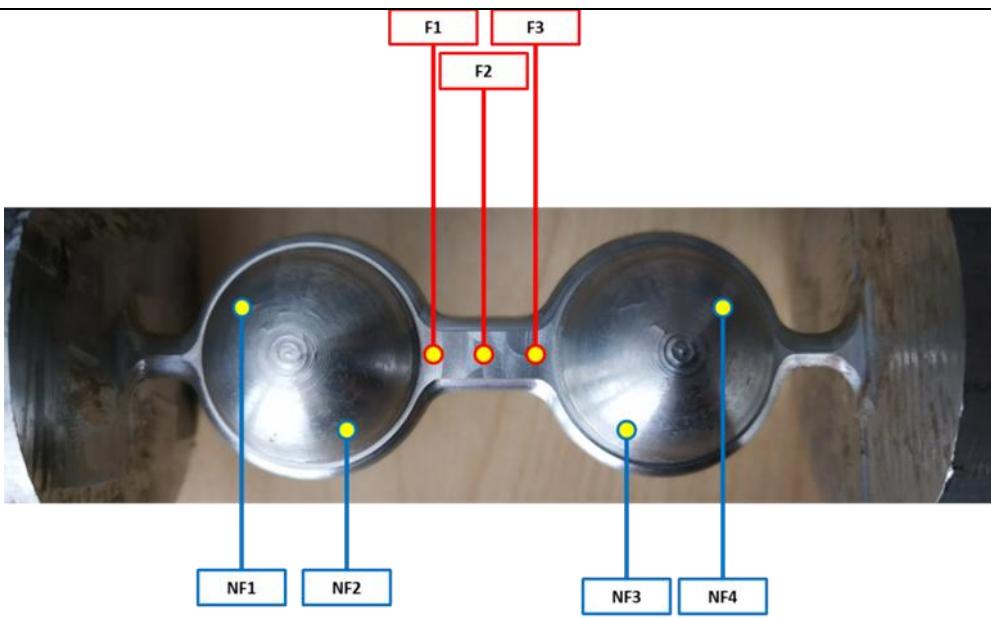
Figure 4.11 Surface roughness assessment results: Toy Jack

Table 4.7 Surface roughness assessment results: Alphabet S



Model	Surface Inspection Points	Experiment 1		Experiment 2		Experiment 3	
		Ra Value (µm)	Average (µm)	Ra Value (µm)	Average (µm)	Ra Value (µm)	Average (µm)
Alphabet S	Side A	F1	0.215	0.265	0.331	0.297	0.218
		F2	0.324		0.312		0.232
		F3	0.346		0.276		0.143
		F4	0.255		0.268		0.242
		F5	0.186		0.298		0.154
	Side B	F1	0.157	0.192	0.308	0.303	0.262
		F2	0.224		0.325		0.213
		F3	0.139		0.317		0.179
		F4	0.223		0.326		0.285
		F5	0.216		0.239		0.278
	Side A	NF1	1.322	1.257	1.329	1.240	0.898
		NF2	1.278		1.102		0.900
		NF3	1.345		1.163		0.956
		NF4	1.084		1.365		0.907
	Side B	NF1	0.902	0.887	1.129	1.014	0.991
		NF2	0.815		0.907		0.938
		NF3	0.829		1.156		0.830
		NF4	1.003		0.865		0.793

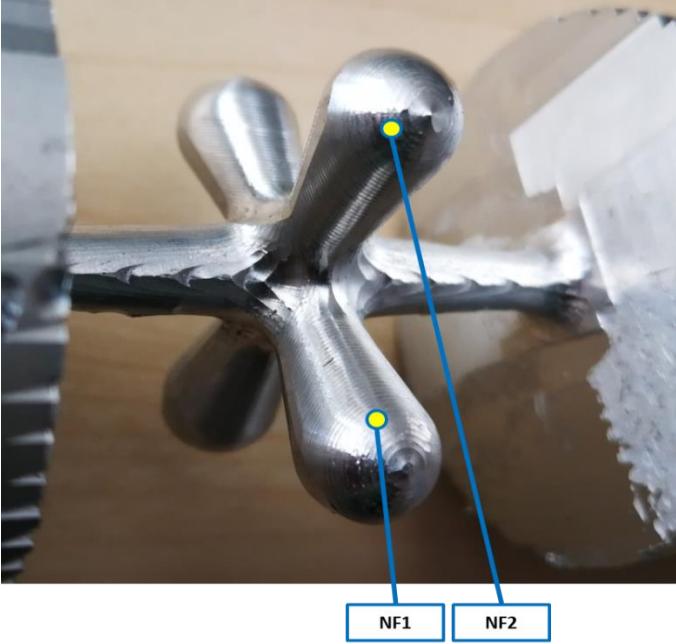
Table 4.8 Surface roughness assessment results: Baby Toy



The photograph shows a Baby Toy with two circular faces. Four inspection points are marked with yellow dots and labeled NF1, NF2, NF3, and NF4. Red lines connect these points to blue boxes at the bottom of the image, which are labeled F1, F2, F3, NF1, NF2, NF3, and NF4. Above the toy, three more points are labeled F1, F2, and F3, connected by red lines to blue boxes at the top.

Model	Surface Inspection Points	Experiment 1		Experiment 2		Experiment 3	
		Ra Value (µm)	Average (µm)	Ra Value (µm)	Average (µm)	Ra Value (µm)	Average (µm)
Baby Toy	Side A	F1	0.349	0.395	0.253	0.321	0.304
		F2	0.308		0.360		0.228
		F3	0.527		0.351		0.316
	Side B	F1	0.252	0.239	0.304	0.376	0.328
		F2	0.346		0.367		0.294
		F3	0.118		0.456		0.235
	Side A	NF1	0.932	0.806	0.750	0.759	0.626
		NF2	0.747		0.746		0.740
		NF3	0.775		0.711		0.562
		NF4	0.769		0.827		0.700
	Side B	NF1	0.675	0.800	0.793	0.821	0.749
		NF2	0.826		0.678		0.713
		NF3	0.759		0.871		0.578
		NF4	0.939		0.943		0.712

Table 4.9 Surface roughness assessment results: Toy Jack



Model	Surface Inspection Points	Experiment 1		Experiment 2		Experiment 3	
		Ra Value (μm)	Average (μm)	Ra Value (μm)	Average (μm)	Ra Value (μm)	Average (μm)
Toy Jack	Side A	NF1	0.956	0.903	0.798	0.761	0.723
		NF2	0.849		0.724		0.695
	Side B	NF1	0.955	0.935	0.692	0.698	0.761
		NF2	0.915		0.704		0.618
	Side C	NF1	0.893	0.902	0.810	0.787	0.782
		NF2	0.911		0.764		0.731
	Side D	NF1	0.810	0.802	0.807	0.802	0.658
		NF2	0.793		0.796		0.718

CHAPTER 5

CONCLUSION

5.1 Introduction

This chapter summarizes the investigation of machining simulation routines by using visual basic programming in NX CAM system. The research was conducted to investigate the capability of programming codes to handle machining simulation routines in modern CAM system. An experiment was designed to identify the optimum cutting orientation and correlation of cutting approaches toward parts quality and accuracy in 4 axis milling machining.

5.2 Conclusions

The thesis proposed the development of simulation application to assist the 4 axis CNC machining operation in NX CAM systems. The simulation applications are developed through Visual Basic Programming, NX CAM and VERICUT tools. There are several important parameters being analysed by the applications. This includes cutting angle for roughing operation, cutting tools size and type for different surfaces and optimum combination of axial depth of cut (ADOC) and radial depth of cut (RDOC) in finishing operation. The estimated time to perform process planning activities are measured and compared between conventional and proposed method. The optimum parameters proposed by the application are further validated through machining several models consist of different features and sizes. A RoughSimulCAM and FinishSimulCAM application offers another solution to execute the simulation routines in CAM environment. Integration of Visual Basic programming language in NX CAM system manages to optimize the process planning and able to execute multiple simulation routines effectively. This approach is considered as an alternative way to determine an optimum cutting orientation and cutting parameter in 4 Axis machining processes. As conclusions, the developed program managed to improve the efficiency of simulation routines and shorten the processing time in CAM system. The achievement of simulation and experiment carried out through this research have

fulfilled the objectives that stated in the beginning of the thesis. The research objectives can be summarized in further details as follows:

Objective 1: To study the implementation of programming codes in CAM systems by developing a customized program to perform the simulation processes.

In this research, several approaches have been discussed in chapter 3.3 on the method employed to develop a customize applications through visual basic programming. In NX CAM systems, there is a function called NX Journaling which is a tool to record and translate user interaction into programming code. This code is then customized through Visual Basic Programming to build up a special script for executing specific functions. There are four methods employed in the customization of the coding which are Grouped Code, Replacement Code, Simulation Instruction Code and Data Exportation Code. Each method has been explained in details in chapter 3.3. Based on the simulation assessment in chapter 4.1, the developed applications manage to improvise the overall processing time to construct machining operation from 22.50 min improve to 5.11 min, which is equal to 77.3% improvement. This clearly shows that the effectiveness of the integration of application programming interface into CAM systems.

Objective 2: To analyse the applicability of the developed application in simulating 4 axis machining operations using several CAD models.

The developed simulation applications, called RoughSimulCAM and FinishSimulCAM has been validated and discussed further in chapter 4.2. RoughSimulCAM is an application to execute roughing operation where the main input parameter is consisting of set of orientation and initial cutting angle. FinishSimulCAM is an application developed to execute finishing operation where the main input is Depth of Cut (Radial and Axial). The evaluation is carried out on 10 models with various geometry and surface features. Based on the simulation, it shown that the developed application manages to execute the simulation routines for all selected model.

Objective 3: To further validate the approach through machining experiment based on optimum results obtained in simulation study.

A real machining experiment is needed in this research in order to validate the functionality of developed simulation application. The assessment criteria are more on the actual volume removed (compared to simulation) and surface roughness. There are three experiments carried out. Each experiments parameter was selected based on minimum, median and maximum volume removed. In this experiment, three different models are selected, Alphabet S, Baby Toy and Toy Jack. According to the experiment results, volume removed assessment shows the deviation between simulation and real experiments is less than 0.7% and it is acceptable since the deviation is lower than 1.0%. In terms of surface roughness, overall experiment shows that the roughness value falls below 1.0 μ m, which is considered under good surface finish for machining processes.

5.3 Limitations and Recommendations

Throughout the study, there is a few limitations that need to be acknowledged. First, there is a few type of operation for machining simulation in NX-CAM software, such as “mill_planar”, “mill_contour”, “mill_multi-axis” and “mill_rotary”. The simulation application built in this research is only applicable for “mill_contour” operation type. This is because the operation of 4 axis machining that conducted within few cutting angles to complete the whole operation. For example, RoughSimulCAM used to identify optimum cutting orientation for high material removal in roughing operation. It requires at least three cutting angle for one complete machining cycle. Each cutting angle will have left remaining material that will be removed by the next cutting angle. By using “mill_contour” operation type, there is an operation sub-type called “Rest Milling” which is feasible to fulfil this requirement. Machining simulation performed for finishing simulation (FinishSimulCAM) is also considered as time consuming. Depending on the range of parameter and the complexity of the models, the simulation may run up to 30 minutes approximately. This is because FinishSimulCAM approach will run all the experiments with different combination of Axial Depth of Cut (ADOC) and Radial Depth of Cut (RDOC). Each experiment (total of nine experiments) consists of four roughing operations and four finishing operations. The simulation approach will re-builds all these operations for each experiment with parameters value defined by user earlier. However, the finishing simulation still can be executed with random parameters.

based on user preferences since the application is built with flexible inputs at predetermined ranges.

There are few possible areas for further improvement in CNC machine simulation routines. First, the developed application required several inputs to be defined by user before starts the simulation. Since the source code behind the GUI have few information that can be referred, therefore it has possibility to integrate all of this information with some minor calculation to minimize the input require from user. For example, the cutting tools size can automatically be defined based on the workpieces diameter. Second, the cutting parameter embedded in RoughSimulCAM application only applicable for aluminium material. In general, the cutting parameter for machining processes influenced by the type of material to be machined. Therefore, there is a need to build up so called “Cutting Parameter Database” inside the application, so that the capability of RoughSimulCAM application can be extended further to other materials. Lastly, in future, the application should be able to be implemented for others type of machining such as turning and drilling. In this study, Visual Basic Programming was used as the platform to customize the back-end of the application and to develop graphical user interfaces (GUI) for front-end user. Other programming tools such as C++, C# and VB.NET also can be explored to improvise and enhance the accuracy of the simulation and results.

As a conclusion, this study successfully investigates the simulation routines in CNC machining and improvise the process. RoughSimulCAM offer the simulation to defined optimum cutting angle with maximum volume removed while FinishSimulCAM used to defined optimum depth of cut parameter to achieve maximum volume removed for different machined models. In summary, machining simulation application developed through this research manages to minimize the time consumed to execute simulation routine in NX CAM up to 77.3% compared to manual approach.

5.4 Publications

Publications emerging from this thesis are stated as follows:

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APPENDICES

Appendix A: ROUGHSIMULCAM PROGRAM CODING

FORM LOAD CODING

```
Private Sub Form3_Load(sender As System.Object, e As System.EventArgs) Handles MyBase.Load

    workpiecediameter.Text = "50"
    orientationR01.Text = "0"
    RoughTD01.Text = "10"
    depthofcut01.Text = "2.0"
    orientationF01.Text = "0"
    FinishTD01.Text = "5"
    CheckBox1.Checked = False
    partname.Enabled = False
    textBox1.Enabled = False
    textBox2.Enabled = False
    textBox3.Enabled = False
    textBox1.Text = "0"
    textBox2.Text = "360"
    textBox3.Text = "180"
    finishing_4.Checked = True

    folder1 = "C:\#NX_Program_Export"

    If Not Directory.Exists(folder1) Then
        Directory.CreateDirectory(folder1)
    End If

End Sub
```

ROUGHING SIMULATION CODING

```
Private Sub Button1_Click(sender As System.Object, e As System.EventArgs) Handles Button1.Click

    If roughing_4.Checked Then

        If CheckBox1.Checked = False Then
            roughing4ONLY()
        Else
            roughing4()
            roughing4simulation()
        End If

    ElseIf roughing_3a.Checked Then

        If CheckBox1.Checked = False Then
            roughing3aONLY()
        Else
            roughing3a()
            roughing3asimulation()
        End If

    ElseIf roughing_3b.Checked Then
```

```

    If CheckBox1.Checked = False Then
        roughing3bONLY()
    Else
        roughing3b()
        roughing3bsimulation()
    End If

End If

End Sub

Private Sub roughing4simulation()

    Dim a As Integer
    Dim b As Integer
    Dim c As Integer

    Dim totalCuttingLength As Double
    Dim totalCuttingTime As Double
    Dim MRR As Double

    Dim saveData(360, 4) As Double
    Dim cData As Integer = 1

    a = textbox1.Text
    b = textbox2.Text
    c = textbox3.Text

    For value As Integer = a To b Step c
        roughing4_press(value, totalCuttingLength, totalCuttingTime, MRR)

        saveData(cData, 1) = value 'value
        saveData(cData, 2) = totalCuttingLength 'totalCuttingLength
        saveData(cData, 3) = totalCuttingTime '/ 1000 'totalCuttingTime
        saveData(cData, 4) = MRR * totalCuttingTime

        System.Threading.Thread.Sleep(1000)
        Application.DoEvents()

        cData = cData + 1

    Next
    WriteValueToExcel_roughing4(cData, saveData)

    Me.Close()
    Form1.Close()

End Sub

```

Appendix B: FINISHSIMULCAM PROGRAM CODING

FORM LOAD CODING

```
Private Sub Form5h_Load(sender As System.Object, e As System.EventArgs) Handles MyBase.Load

    workpiecediameter.Text = "50"
    orientationR01.Text = "0"
    RoughTD01.Text = "10"
    depthofcut01.Text = "2.0"
    orientationF01.Text = "0"
    orientationF02.Text = "90"
    orientationF03.Text = "180"
    orientationF04.Text = "270"
    FinishTD01.Text = "5"
    spindlespeed02.Text = "3000"
    feedrate02.Text = "400"
    width.Text = "25"
    depth1.Text = "5"
    CheckBox1.Checked = False
    partname.Enabled = False
    Button1.Enabled = False

    w1.Text = "5"
    w2.Text = "10"
    w3.Text = "15"
    w4.Text = "20"
    w5.Text = "25"
    w6.Text = "30"
    w7.Text = "35"
    w8.Text = "40"
    w9.Text = "45"

    d1.Text = "10"
    d2.Text = "9"
    d3.Text = "8"
    d4.Text = "7"
    d5.Text = "6"
    d6.Text = "5"
    d7.Text = "4"
    d8.Text = "3"
    d9.Text = "2"

    folder1 = "C:\#NX_Program_Export"

    If Not Directory.Exists(folder1) Then
        Directory.CreateDirectory(folder1)
    End If

End Sub
```

FINISHING SIMULATION CODING

```
Private Sub Button1_Click(sender As System.Object, e As System.EventArgs) Handles Button1.Click

    If freeformfaces.Checked = True And CheckBox1.Checked = False Then
        FreeFormOnly()
    End If

    If freeformfaces.Checked = True And CheckBox1.Checked = True Then
        FreeFormWidthDepthSimulation()
    End If

    If planarandfreeformfaces.Checked = True And CheckBox1.Checked = False
Then
        PlanarFreeFormOnly()
    End If

    If planarandfreeformfaces.Checked = True And CheckBox1.Checked = True
Then
        PlanarFreeFormWidthDepthSimulation()
    End If

End Sub
```

```
Private Sub FreeFormWidthDepthSimulation()

    FreeFormSimulation()

    FreeForm_experiment1(totalCuttingLength1, totalCuttingTime1)
    FreeForm_experiment2(totalCuttingLength2, totalCuttingTime2)
    FreeForm_experiment3(totalCuttingLength3, totalCuttingTime3)
    FreeForm_experiment4(totalCuttingLength4, totalCuttingTime4)
    FreeForm_experiment5(totalCuttingLength5, totalCuttingTime5)
    FreeForm_experiment6(totalCuttingLength6, totalCuttingTime6)
    FreeForm_experiment7(totalCuttingLength7, totalCuttingTime7)
    FreeForm_experiment8(totalCuttingLength8, totalCuttingTime8)
    FreeForm_experiment9(totalCuttingLength9, totalCuttingTime9)

    WriteValueToExcel_freeform()

    Me.Close()
    Form1.Close()

End Sub
```