DEVELOPMENT OF GENERATIVE COMPUTER-AIDED PROCESS PLANNING SYSTEM FOR LATHE MACHINING

AHMAD FAIZ BIN ZUBAIR

UNIVERSITI SAINS MALAYSIA

2019

DEVELOPMENT OF GENERATIVE COMPUTER-AIDED PROCESS PLANNING SYSTEM FOR LATHE MACHINING

by

AHMAD FAIZ BIN ZUBAIR

Thesis submitted in fulfilment of the requirements
for the degree of
Doctor of Philosophy

September 2019

ACKNOWLEDGEMENT

First and foremost, praises and thanks to the Allah SWT, the Almighty, for His showers of blessings throughout my research work to complete the research successfully.

I would like to express my deep and sincere gratitude to my research supervisor, Associate Professor Dr Mohd Salman Abu Mansor, for giving me the opportunity to do research and providing invaluable guidance throughout this research. His dynamism, vision, sincerity and motivation have deeply inspired me.

I am extremely grateful to my parents for their love, prayers, caring and sacrifices for educating and preparing me for my future. I am very much thankful to my wife and my children for their love, understanding, prayers and continuing support to complete this research work. Also, I express my thanks to my parents in law, my sisters, brothers, sisters in law and brother in laws for their support and valuable prayers.

My special thanks goes to my friends and research colleagues for their constant encouragement. I also thank all the staff of School of Mechanical Engineering, Universiti Sains Malaysia for their kindness and support. I thank the management of Universiti Teknologi MARA and Ministry of Education Malaysia for their support of scholarship and study leave. Finally, my thanks go to all the people who have supported me to complete the research work directly or indirectly.

TABLE OF CONTENTS

APPENDICES

LIST OF PUBLICATIONS

LIST OF TABLES

LIST OF FIGURES

Page

LIST OF SYMBOLS

bx	Boundary tolerance in x-axis direction
bz	Boundary tolerance in z-axis direction
β	Attractiveness
α	Randomization parameter
ϵ_i	Vector of randomization
c	Cylindrical SDVF
cn	Conical SDVF
c'	Cylindrical SDVF extension
C_{CF}	Edge complexity for SDVF
C_{CM}	Edge complexity for part model
C_E	Element complexity
C_I	Machine idle cost (RM/piece)
C_M	Cutting cost by actual cutting time (RM/piece)
cm	Edge element
c_E	Edge element
C_R	Cost of tool replacement (RM/piece)
CS	Cutting Speed
CSc	Complexity Scale
C_{SF}	Surface complexity for SDVF
C_{SM}	Surface complexity for part model
C_T	Tool cost (RM/piece)
Cv	Volumetric complexity
CS_r, CS_f	Cutting speeds in roughing and finishing machining (m/min)
CS_{rL}, CS_{fU}	Lower and upper bound of cutting speed in roughing machining (m/min)
CS_{fL}, CS_{fU}	Lower and upper bound of cutting speed in finishing machining (m/min)

d	Depth of cut
d_r, d_f	Depth of cut for roughing and finishing machining (mm)
d_{rL}, d_{rU}	Lower and upper bound of d_r rough machining (mm)
d_t	Total depth of material to be removed (mm)
dz	Edge Z distance
D, L	Diameter and length of the workpiece (mm)
F	Filled combinations SDVF-FR
f	Feed rates
f'	Freeform SDVF extension
f_r, f_f	Feed rates in roughing and finishing machining (mm/rev)
f_{rU}, f_{rL}	Lower and upper bound of f_r (mm/rev)
f_{fU}, f_{fL}	Lower and upper bound of f_f (mm/rev)
F_r, F_f	Cutting forces during roughing and finishing machining (N)
F_u	Maximum allowable cutting force (N)
h_1,h_2	Constants related to travel of cutting tool and approach/departure time (min)
h	Cylinder height
I	Light intensity
k_0	Direct labour cost with overhead (C/min)
k_t	Cost per cutting edge (RM/edge)
k_1, μ, υ	Constants of cutting force Equation
k_2, τ, ϕ, δ	Constants related to chip-tool interface temperature Equation
k_3, k_4, k_5	Constants for roughing and finishing parameter relations
λ, ν	Constants related to the expression of a stable cutting region
n'	Conical SDVF extension
n	Number of rough passes
N_U, N_L	Upper and lower bounds of n
η	Attributes to calculate PMC in the relation of V_{CAD} and ODV_{alg}
ϕ	Ratio of volume complexity to element complexity
δ	Summation of volume complexity to element complexity
ODV_{alg}	Overall Delta Volume that is calculated from the developed algorithm
ODV_{manual}	Overall Delta Volume that is manually calculated from the commercial software

ΔODV	The percentage differentiation between ODV_{alg} and ODV_{manual}
pl	Planar SDVF
p'	Planar SDVF extension
p, q, r, C_0	Constants of tool-life Equation
P_r, P_f	Cutting power during roughing and finishing machining (kW)
P_U	Maximum allowable cutting power (kW)
$P_{n.z}$	Vertex of edge in z-axis direction
Q_r, Q_f	Chip-tool interface roughing and finishing machining temperatures (°C)
Q_U	Maximum allowable chip-tool interface temperature (°C)
q	A weight for T_p [0, 1]
R	Nose radius of cutting tool insert (mm)
Rx, Ry, Rz	Rotations in x, y and z-axis directions
r	Radius of the cylinder
r_{torus}	Radius of torus
r_c	Radius of circular edge e1 and e2
S	Combine SDVF
SC	Stable cutting region constraint limit
sf	Surface element
SR_U	Maximum allowable surface roughness (mm)
sm	Surface element
t	Finishing thickness
T, T_r, T_f	Tool life expected tool life for roughing machining, and expected tool life for finishing machining (min)
T_p	Tool life of weighted summation of T_r and T_f (min)
T_U, T_L	Upper and lower bounds for tool life (min)
θ	Rotational angle
UPC	Unit production cost except for material cost ($)
V_{CAD}	CAD part model volume
V_s	Stock model volume
w	Total number of data unit to calculate PMC.
x', y', z'	New x, y and z positions for part model rotations

LIST OF ABBREVIATIONS

ACAPP	Automated Computer Aided Process Planning
ACIS	Name of 3D software developed by Spatial company
ACO	Ant Colony Optimization
AFR	Automatic Feature Recognition
ANN	Artificial Neural Network
API	Application Programming Interface
BZT	Bilinear Transformation Method
CAD	Computer-aided Design
CAIP	Computer-aided Inspection Planning
CAM	Computer-aided Manufacturing
CAPP	Computer-aided Process Planning
CNC	Computer Numerical Control
DfC	Design for Costing
EXCATS	Expert Computer Aided Tool Selection System
ERP	Enterprise Resource Planning
FA	Firefly Algorithm
FBM	Feature-based Method
FSC	Feature Shape Complexity
FTL	Flexible Transfer Line
FPO	Flower Pollination Optimization
GA	Generic Algorithm
IDEF0	Integrated Definition for Function Modelling
ISO	International Organization for Standardization
MPF	Media Package File
MCU	Machine Control Unit
NC	Numerical Control
ODV	Overall Delta Volume
PSO	Particle Swarm Optimization
PMC	Part Model Complexity
SDV	Sub-delta Volume
SDVF	Sub-delta Volume of Finishing

SDVF-FR	Sub-delta Volume of Finishing-Filling Region
SDVR	Sub-delta Volume of Roughing

PEMBANGUNAN SISTEM PERANCANGAN PROSES BERBANTUKAN KOMPUTER SECARA GENERATIF UNTUK PEMESINAN LARIK

ABSTRAK

Perancangan proses berbantukan komputer (CAPP) adalah penghubung di antara lukisan berbantukan komputer (CAD) dan proses pembuatan berbantukan komputer (CAM). CAPP berfungsi dalam proses pengecaman input geometrik dari CAD dan menganalisanya ke dalam fungsi khusus untuk tujuan permesinan di dalam CAM. Fungsi ini sentiasa membuat takrifan data yang tidak teratur dalam bekalan CAD dan permintaan daripada sistem CAM. Kajian ini adalah percubaan untuk menyelesaikan masalah ini dengan mengenal pasti model bahagian berasaskan isipadu geometri dan menghasilkan isipadu sub-delta yang kemudiannya boleh digunakan untuk menghasilkan data berasaskan ciri pembuatan untuk CAM dalam sistem tunggal melalui penjanaan algorithma yang di bina melalui perisian '3D modeller' bersumber terbuka. Untuk memaparkan isipadu sub-delta yang dicam dan proses pemesinan, "part model complexity" (PMC) diperkenalkan. Perbezaan jumlah keseluruhan delta (ΔODV) dikira dan pengesahan PMC yang dicadangkan telah dilakukan. Seterusnya, bagi meminimakan kos produksi seunit, parameter-parameter termasuk kelajuan pemotongan (*CS*), laju suapan (*f*) dan kedalaman potongan (*d*) dioptimumkan melalui algoritma kelip-kelip (FA) dan berguna dalam pemilihan mata alat dan penjanaan laluan mata alat. Keputusan dari pengecaman ciri automatik menunjukkan kurang dari 0.02% ralat berbanding keseluruhan delta keseluruhan algoritma, (ODV_{alg}) dan pengiraan manual ODV, (ODV_{manual}). Untuk mengesahkan laluan mata alat yang dijana, G-code dalam format pakej fail media (MPF) dijana dan dijalankan melalui mesin CNC larik. Pembangunan algoritma ini membuktikan bahawa kos unit produksi yang minimum boleh dicapai. Pembangunan sistem ini dibuktikan dapat memindahkan data CAD ke arah proses pemesinan yang diterjemahkan dalam bentuk CAM.

DEVELOPMENT OF GENERATIVE COMPUTER-AIDED PROCESS PLANNING SYSTEM FOR LATHE MACHINING

ABSTRACT

Computer Aided Process Planning (CAPP) is the bridge between computer-aided design (CAD) and computer-aided manufacturing (CAM). CAPP functions as the recognizer of the geometric input from CAD and analyse it into specific function for manufacturing purpose in CAM. These functions always create irregular data descriptions in current CAD and CAM system supply and demand. This study attempts to solve this problem by recognizing the part model's features via its geometrical based and produce sub-delta volumes that can later be used to generate manufacturing feature-based data for CAM in a single system via generations of algorithm through open source 3D CAD modeller. To map the generated sub-delta volume and respective machining process, part model complexity (PMC) is introduced. Errors of the overall delta volume (ΔODV) were calculated and verification of the proposed PMC is done. Furthermore, to minimize unit production cost, machining parameters including cutting speed (*CS*), feed rate (*f*) and depth of cut (*d*) were optimized for regular form surfaces by using firefly algorithm (FA). These parameters were then useful for tooling selections and tool-path planning. The results from the automatic feature recognitions show less than 0.02% of error in comparison of algorithm overall delta volume, (ODV_{alg}) and the manual calculation ODV, (ODV_{manual}). To validate the generated tool-path, G-codes generated in media package file (MPF) file format and verified through CNC lathe machine. Indeed, the developed algorithm was able to determine the minimum unit production cost of lathe machining part model. Therefore, a single

automatic system that able to transfer CAD data into machining readable data through CAM data had been developed.

CHAPTER 1

INTRODUCTION

1.1 Research overview

In the world that supporting Industry 4.0, every aspect of digitizing production or manufacturing based industries is attractive to researchers. Towards digitisation transformation that is driven by connected technologies, automation at the production level is becoming priority. Smart manufacturing systems or smart factory could not avoid the use of computers in doing its activities. In design stage, Computer-aided design (CAD) becomes essential tool for designers to design part model before going into productions. In manufacturing stage, Computer-aided manufacturing (CAM) is used. These two tools are much likely to be called together as CAD/CAM technologies. These developments were pioneered by the General Motors Research Laboratories in the early 1960s. It is among the fastest growing technology in the world and it is made possible by the development of mass-produced silicon chips and the microprocessor (Ames, 2000). The ongoing development of the simulation of many manufacturing processes is one of the keys means by which CAD/CAM systems are becoming increasingly assimilated. CAD/CAM systems also assist integration among those involved in design, manufacturing, and other processes. This is becoming extensive when one company appoints another to either design or produce a component. Thus, making data sharing becoming more complicated.

Process planning is an essential activity that convey design information of a product into manufacturing instructions to produce it into real product (Al-Wswasi et al., 2018). This activity includes features extraction and recognition, process selection, machining operation sequence, cutting tool selections, cutting parameters determinations, tool-path generations and many more. Figure 1.1 shows the architecture of smart manufacturing system (Al-Wswasi et al., 2018). To bridge design process and manufacturing process which available in various format, CAPP is needed. Because of many processes need to be done, a proper features extraction and recognition technique have to be implemented in order to accomplish the requirement of the production. Moreover, because of many processes or systems involved, data transfer and exchange are complicating the process flow. Therefore, a system that consist of different systems acting as a bridge in connecting design and the production of workpieces is needed to solve the issue. This study attempts to solve the problem in developing the tool-path of a selected feature that had been decomposed by a computer-aided design (CAD) part model.

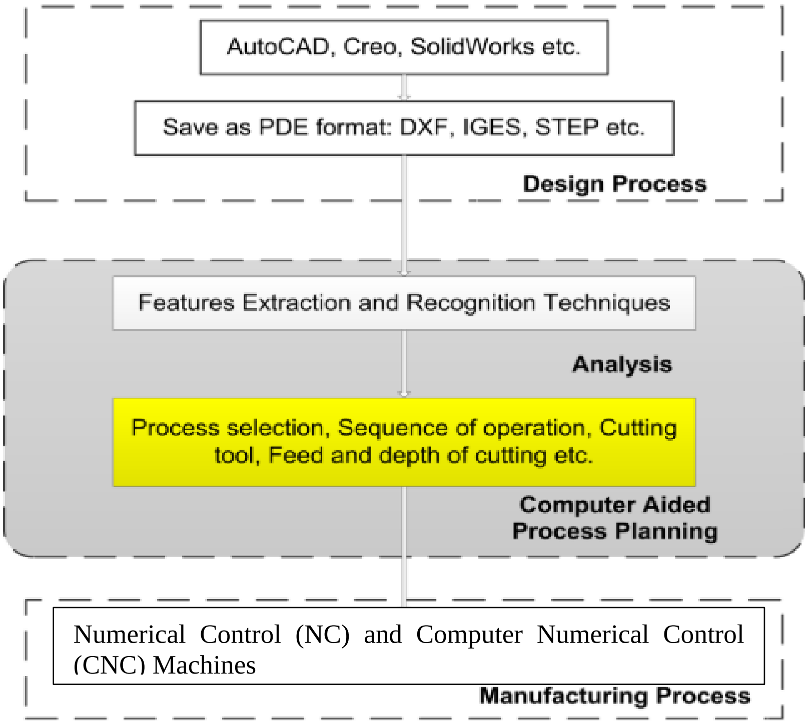

Figure 1.1 The architecture of smart manufacturing system where Computer Aided Process Planning (CAPP) system as the bridge between CAD and CAM.

Issues relating to the generation of process planning of lathe machining workpiece including the efficiencies of the feature recognitions, the recognitions of freeform features of cylindrical part model, machining parameters optimization and tool-path generations gave motivation to the study in developing an automatic system that enable users to generate tool path of a workpiece model within a single click. The system will produce an output in order to the part to be machined.

1.2 Problem statement

To support machining of a CAD part model, CNC machining is one of the best options to expedite the production time. However, in conveying part model information from CAD to CAM system, different product data descriptions especially in sequencing machining features into generating its tool-path for machining is quite challenging. Therefore, a system to bridge the CAD and CAM system is needed. The system needs to cater the bridging systems in CAPP that can be read by both CAD and CAM. CAD part model features has to be recognized in a way that manufacturing features can be suited and delivered to the production of the part model.

One of the CAM function in CNC is by contributing to CNC lathe machining. Although, any studies had been done for feature recognition of mill-turn part model, however, cylindrical part model has its own challenge. Being cylindrical means the part model consists of different topological data compare to non-cylindrical part model. The topological data of cylindrical part model especially when convex and concave surfaces are detected need different treatment and cannot directly used the same algorithm as non-cylindrical part model. This been highlighted by Bok & Abu Mansor (2012) and Sakurai (1992). Therefore, requires different approaches to extract the features. The nature of cylindrical faces that have different vector directions obviously needs different approach especially when dealing in the decompositions of new volumes.

This study is introducing an algorithm developed to cater the problem of transferring data of CAD part model in making it able to be machined by lathe machining. This algorithm is trying to solve the problem by having an automatic single system from feature recognition into tool-path generation mainly for cylindrical part model.

1.3 Objectives

This study attempts to solve the problems by developing a system that consist of the following objectives:

1. To automatically recognize and decompose regular and freeform geometry features of symmetrical and non-symmetrical cylinder part using volume decomposition method.

2. To determine the complexity of part model through the recognition of the regular and freeform features and delta volume generations.

3. To optimize turning machining parameters and cutting tool selections through the embedding of firefly algorithm in minimizing machining cost.

4. To establish sequence of the lathe machining features for turning tool-path generations and compare with commercial system tool-path generation.

1.4 Scope of research

The research focus on generative CAPP for lathe machining part model. Generations of the decomposed features consist of regular and freeform features. Part model features including the internal features will determine the complexity of the part model. Although most CAD features can be automatically recognized, this study only focus on most regular turning machining features but not boring, knurling and threading. These include the selections of the cutting tool. Cutting tools selection will involve inserts selections based on its International Organization of Standards (ISO) code and the preferable tool inserts of this thesis came from Sandvik Coromant tool manufacturer. The generative CAPP system is a one system develop in C++ language using ACIS CAD modeller command.

1.5 Thesis Outline

This thesis is structured in a way to make reader easy to capture the information. This thesis consists of five chapters. Each chapter starts with an introduction of the chapter and every section after the introduction section are the main information of the study. Mainly the next section will begin with Automatic feature recognitions (AFR) of regular form features, then continue with regular-freeform features, part model complexity, parameters optimizations, cutting tool selections, automatic sequencing and tool-path planning. Every chapter will follow the same sequence and suit every chapter purpose.

This chapter is the introduction chapter which includes research overview, problem statement, objectives, scope of research and thesis outline sections. Mainly the core aspect and the motivations of the study are described in this chapter.

Chapter 2 is the literature review chapter. The review of the main topics of the research is describe in different sections. These sections include the Introduction, AFR, Regular-freeform revolved surface, part model complexity evaluations, multi-objectives optimization, cutting tool selections, automatic sequencing of machining, tool-path planning and related commercial software. At the end of the chapter a section to summarize the research gap is presented.

Chapter 3 presents the methodology chapter. This chapter represents the methods and approaches used in conducting the research. It is organized in sections according to the literature review sections sequences.

Chapter 4 represents the result and discussion chapter; this chapter includes eight case studies that include all the finding from the methods and approaches being developed. Each case study is discussed in detail.

Chapter 5 is the last chapter and the conclusions of the study are presented.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Different data descriptions were among one of the disadvantages found in CAPP (Xionghui et al., 2007). This problem leads to the need for human intervention in pertaining to manufacturing information from CAD data (Abouel Nasr & Kamrani, 2006). One of the solutions to pursue original geometry data in recognizing features is feature-based technology (Deja & Siemiatkowski, 2013). Volume decomposition of recognized features which consider direct information of CAD geometry and topology data were extracted and generate bodies with the similar volume of material that needs to be removed from the stock model (Bok & Abu Mansor, 2012; Kataraki & Abu Mansor, 2016). These volumes called SDV which are in geometry-based information can be used for further determination of manufacturing requirements (Kataraki & Abu Mansor, 2018). To deal with the information needed from CAD data, open source CAD software such as ACIS via .SAT file format can provide geometrical and topological data of the intended features for further development of CAPP system (Kim & Mun, 2015; Kwon et al., 2015, 2016; Zubair & Abu Mansor, 2018). With the information retrieved, process plan can be generated. Process plan is a document that provide information for manufacturing or fabrication purpose. An example of manual process planning can be seen in Machining Cloud (2016) which total of eight decisions a planner needs to decide.

CAPP is required to bridge CAD and CAM. It provides useful information to convert a design into a producible part economically and competitively (Al-Wswasi et al., 2018; Xu et al., 2011; Yusof & Latif, 2014). Information such as machining sequences, cutting tool selections, tool path generation that is conventionally provided by the

CAM system can now achievable in a single CAPP system. A good CAPP system starts with the recognition of geometrical and topological data of the part model and utilizing these data to suit machining or manufacturing purposes. Therefore, resulting in excellent and efficient production’s result compare to the traditional approach that requires good experience and knowledge of manufacturing experts to solve process planning issues.

CAPP system started to develop since the 1980’s (Marri et al., 1998). It is reported that generative CAPP is more popular than the variant CAPP system. In the 1990’s CAPP system evolve to suit more advanced technology that includes NC machining (Eversheim & Schneewind, 1993) and hybrid processes (Zhu et al., 2013). It continues to evolve and much high-level decision-making methods are used including Artificial Neural Network (ANN), Petri nets, fuzzy set theory, the knowledge-based and genetic algorithm (Xu et al., 2011). However, based on a recent study, there is still room of improvement in CAPP system in the form of automatic computer-aided process planning (ACAPP) to bring it to the next level (Al-Wswasi et al., 2018). This is because many researches had done it in not fully system. It is intending to cater only certain processes of CAPP and mostly dealt with the feature recognitions approaches. The extended study of CAPP was much established in STEP-NC approaches (Yusof, 2010). The study recognized features from CAD in STEP format and convert it toward CNC machining features. STEP format provide data in text description. From feature recognitions, works had been devoted until the CNC machining adaptations (Wang et al., 2007a). An ISO standards had also been established (Yusof, 2010). Furthermore the standards was also implemented for based nonlinear process planning (Dae-Hyuk Chung, 2008).

2.2 Computer-Aided Process Planning

Process planning is defined as the activity of determining which manufacturing processes and machines should be used to accomplish the numerous operations needed to produce a workpiece. On the other hand, process planning is the systematic solution of the detailed methods by which parts can be produced from raw material to end product. In recent years, CAPP has been recognized as a significant element in computer integrated manufacturing (CIM). CAPP is is the use of computer technology to aid in the process planning of a part or product, in manufacturing. CAPP is the link between CAD and CAM in that it provides for the planning of the process to be used in producing a designed part (Engelke, 1987).

The integration of CAD, CAPP, and CAM is important to accomplish an efficient manufacturing process (Marri et al., 1998). The CAPP system can be in variant type or generative type. In variant CAPP, human intervention is needed to do part classification and part information input, and also to perform required modifications in retrieving similar process plan whereas very little human intervention is required to generate process plans in generative CAPP (Marri et al., 1998).

To conclude, CAPP is a decision-making process. It determines a set of commands and machining parameters essential to manufacture a part. Data research is a necessary step for gaining appropriate product definitions for the CAPP system. This can be carried out after the CAD system is finalized. After the completion of data preparation, the data is entered into CAPP system and it need to be supported by knowledge and physical guidelines. When the CAPP operation is done, the subsequent step is output. From this output, the operation of post processing is done which prepares data for production planning and scheduling activities. Finally, the production planning and scheduling operations are done. The post processing can be an input for the manufacturing element such as machine to be run.

2.2.1 Variant approach

Variant approach also known as retrieval approach which uses a group technology (GT) code to get a generic process plan from the remaining master process plans developed for respectively part family and the edits to suit the necessities of the part (Yusof & Latif, 2014). The variant approach is normally executed with GT coding system. Here, the parts are divided into groups according to similarity, and each group has their own master plan. The advantages of this approach are that the maintenance is easy, but the absence of an on-time calculation of manufacturing process and quality of the process plan still hinge on the knowledge of a process planner. This approach also still requires manual inputs for the formation of the mass data into manufacturing processes (Yusof & Latif, 2014).

2.2.2 Generative CAPP

In this approach, a process plan for individually component is formed from scratch without human intervention. These systems are intended to automatically produce process data to develop a process plan for a part. These systems hold the logic to use manufacturing database and suitable part description systems to generate a process plan for a certain part (Yusof & Latif, 2014). Generative approach abolishes disadvantages of the variant approach and links the gap between the CAD and CAM. The disadvantages of this approach are the difficulty in finding useable features and the complexity in representing, managing, and utilizing human expertise. A generative CAPP system is composed of functions such as (i) machining feature recognition, (ii) machining operation type selection, and (iii) process optimization (Yusof & Latif, 2014).

To fulfill the objectives of the study, generative CAPP system will be considered to be developed. The system must enable the function from part recognitions until the machining operation.

2.3 Lathe Machining

Machining is one of the most significant material removal methods in manufacturing industry. An important machine that is beneficial in machining is the lathe machine. Lathe is one of the broadly used machine tools all over the world. It is commonly acknowledged as the mother of tool room. A lathe machine is normally used in metal spinning, metalworking, woodturning, and glass working. The components of Lathe are:

a. Bed which usually a horizontal beam that clutches the chips and the swarf’s.
b. Headstock that comprises the high precision bearings which hold the horizontal axle known as the spindle.
c. Spindle. This is a hollow horizontal axle with interior and exterior threads on the inboard.
d. Tailstock which is the counterpart of the headstock which has a non-rotating barrel that can slide in and out straight in line with headstock spindle parallel to the axis of the bed.
e. Carriage, that composed of a saddle and an apron and is used as a mount to the cross-slide.

f. Cross-slide, that is a flat piece that sits transverse on the bed which can be moved at right angles with the bed.
g. Tool post, that sits on top of the cross-slide and holds the cutting tool in place, and
h. Tool rest. A horizontal area in line with the spindle and the tailstock from which hand tools are braced against and levered into the workpieces.

Different operations performed on lathe are plain turning, facing, parting, drilling, reaming, boring, knurling, grooving, threading, forming, chamfering, filling, polishing and, taper turning. To suit the machining processes, features or the segments involved from CAD model need to be recognized and can be defined as machining features. Machining feature can be defined as a set of surfaces of the part that can be machined by a single cutter in the same setup or modelled through manufacturing-oriented classes (Chu et al., 2012). Almost all CAPP systems are based on machining features or require machining features to be the input data (Xu et al., 2011). Therefore, many works have been done to describe machining features that have been designated as a volume, a set of surfaces, or a set-information feature related to geometry and topological data.

2.4 Topological data

Topology is a group of rules that, coupled with a set of techniques and editing tools, allow the geodatabase to more accurately model geometric relationships. A topology is kept in a geodatabase as individual or more relationships that outline how the features in one or more feature classes share geometry. The features contributing in a topology are still simple feature classes. Rather than altering the definition of the feature class, a topology helps as a description of how the features can be spatially associated.

Topology has been an essential requirement for data management and integrity. In general, a topological data model enables to spatial relationships by representing spatial objects (point, line, and area features) as a primary graph of topological primitives such as nodes, faces, and edges. These primitives, together with their relations to one another and to the features whose boundaries they embody, are defined by representing the feature geometries in a planar graph of topological data.

Topology is basically used to certify data quality of the spatial relationships and to aid in data collecting. Topology is also used for studying spatial relationships in many conditions, such as dissolving the boundaries between adjacent polygons with the same characteristic values or crossing a network of the elements in a topology graph.

Topology can also be used to model how the geometry from several feature classes can be unified. It is also known to this as vertical integration of feature classes. Features also can share geometry within a topology.

Workpiece that is machined by lathe is a workpiece that is symmetry about the lathe axis. Normally the workpiece machined by lathe machining is in cylindrical shape. In some areas of geometry and topology of the term cylinder denotes to a cylindrical surface. A cylinder is defined as a surface comprising of all the points on all the lines which are parallel to a specified line and which pass through a fixed plane curve in a plane not parallel to the given line (Albert, 2016). Such cylinders have, at times, been referred to as generalized cylinders. Through each point of a generalized cylinder there passes a unique line that is contained in the cylinder. Thus, this definition may be restated to say that a cylinder is any ruled surface spanned by a one-parameter family of parallel lines. A cylinder having a right section that is an ellipse, parabola, or hyperbola is called an elliptic cylinder, parabolic cylinder or hyperbolic cylinder, respectively (Brannan et al., 1999).

2.5 Automatic feature recognition

Research work on CAPP has been going on for more than five decades (Xu et al., 2011) and still continuing. This massive interest among researchers is due to the evolution of CAD and CAM in the modern market. According to surveys, (Su et al., 2015; Xu et al., 2011; Yusof & Latif, 2014), one of the most adopted methods in CAPP in recognizing features of the part model is feature-based method (FBM) due to its ability to facilitate the representation of various types of part data in a significant form to drive automation (Wang et al., 2007b). FBM had been customized with other methods including rule-based method (Abu & Masine, 2007) and boundary classification method (Ismail et al., 2004, 2005). Apart from that, FBM was also applied to integrate with computer aided inspection planning (CAIP) in order to inspect the planning process (Kamrani et al., 2014).

Focusing on cylindrical parts, besides FBM many researches had applied different methods to recognize features, for example by using STEP AP203 protocol (Oussama et al., 2014). Although method of using STEP AP203 protocol excel, the method sometimes proposed several combinations for the same work piece which lead to time consuming and high complexity process. Features were also extracted from commercial CAD software CATIA V5 using feature generator, and then it is synchronized using ANN method (Deb & Parra-castillo, 2011). Moreover, volumetric approaches of finding the machining features from SolidWorks application programming interface (API) were also taken into consideration (Dwijayanti &

Aoyama, 2014). These features then compute combinations for process plans; nonetheless, generations of these proposed combinations consume a lot of time.

A concept of automatic reasoning was used to distinguish milling and turning features in part model by using self-developed software called AMFA and presented in a tolerance graph (Campbell, 2014). Although the result was excellent, access to the software is limited and complex parts cannot be handled. In contrast, Shiqiao & Shah (2007) made attempt to automatically separate the coupled portions and detect form features as well as user-defined features via a graph and rule-based recognition algorithm. Also an effort was done on recognizing machining features by using rule based on different characteristics specific to feature such as the total number of faces, edges by using Unigraphics software (Abu & Masine, 2007). However, in this method, part recognition became more difficult as the number of features increased. Moreover, data exchange (not only to geometry, but also to additional information such as dimensions, dimensional and geometrical tolerances and surface roughness), between different computer systems were being focused (Chlebus & Krot, 2016).

Younis & Abdel Wahab (1997) proposed a CAPP system on metal turning machine by choosing over variant-group technology-process planning. While Su et al. (2015) used hybrid genetic algorithm to plan for turning machining. Apart from that, features were also being recognized by identifying part model’s loops (Yih et al., 2016). Previously, volumetric decomposition method was used for milling machine (Bok & Abu Mansor, 2012; Kataraki & Abu Mansor, 2016, 2018; Sheen & You, 2006) and metal stamping parts (Gupta & Gurumoorthy, 2012, 2013) that consist of regular and freeform features. Although works on volumetric decomposition on regular and freeform shapes produce decent results, but recognition for cylindrical parts can still be extended. For example, Bok & Abu Mansor (2012) mentioned in their papers that the methods introduced did not deal with cylindrical surfaces that is not parted. It was also highlighted that this approaches cannot be taken as combined approach for polyhedral and curves surfaces (Sakurai, 1995; Sakurai & Dave, 1996).

In order to verify the extractions of the feature, percentage of differences by comparing the manually calculated delta volume and the one generated by the algorithm was introduce by Bok & Abu Mansor (2012). Bok & Abu Mansor (2012) in their studies shows the percentage of errors to be 4% - 6% differences. Kataraki & Abu Mansor (2016) later introduce SDVs for finishing filling region (SDVF-FR) to reduce the error to 0.001%. This efficient result was implemented for milling tool-path, hence can be an influence factor to be used in this study for lathe part model. The concept of SDVF-FR is to eliminate gaps produced during the generations of volume decompositions bodies that reduces the differences between the algorithm generated and manual calculation.

2.6 Regular-freeform revolved surfaces

The turn parts and mill-turn parts are classified in many ways. In the research works performed so far, mill-turn part features are classified by its geometrical shape. Prismatic features are categorised as one group and features with rotational axis i.e: cylindrical, conical and sphere are as one group (Tseng & Joshi, 1998). Moreover, manufacturing parts are categorised into prisronal part which are parts that have primitive shapes with one common centreline (Waiyagan & Bohez, 2008). By having these categories, milling features (prismatic) and as-lathed features (rotational) were segregated (Campbell, 2014; Liu et al., 2017; Yip-Hoi et al., 2003). Internal features identified by part’s internal loop. These internal features are then eliminated in the early process leading to only as-lathe features to be recognised.

A surface of revolution or a revolved surface is a surface in Euclidean space created by rotating a curve around an axis of rotation (Korn & Korn, 2000). A revolved face can be classified as regular form and freeform type (Shiqiao & Shah, 2007) and based on the geometrical shape of regular form faces and freeform faces, three types of faces are classified: Type I, Type II, Type III. The Type I is cylindrical, conical and planar faces form, Type II is the freeform face and Type III is fillet and chamfer.

Neutral representation (n-rep) is used to recognise interacting and non-interacting features of rotational components resulting in identification of user-defined features (Shiqiao & Shah, 2007). Features were also being recognised by a rule-based system implementing knowledge-based (Long et al., 2004), edge boundary technique (Ismail et al., 2002, 2004, 2005), artificial intelligence (Deja & Siemiatkowski, 2013) and virtual loops (Yih et al., 2016). Beside using generative algorithm technique (Balic et al., 2006), features were recognised by commercial CAD modeller's feature recogniser such as Solidworks (Dwijayanti & Aoyama, 2014), CATIA (Deb & Parra-castillo, 2011) and neutral file like STEP files (Sivakumar & Dhanalakshmi, 2013).

In order to decompose material to be removed from the stock model, the volume decomposition method was introduced (Sakurai & Chin, 1994). Exact volumes of material to be removed were generated and formed the SDVs of decomposed bodies. This method is then extended to suit roughing and finishing processes (Bok & Abu Mansor, 2012; Kataraki & Abu Mansor, 2016) and to suit milling components (Sundarajan & Wright, 2000). Moreover, an effort has been made to recognise uncut regions for electrical discharge machining (Geng et al., 2016). Previous works on recognising regular surfaces of the cylindrical part model are presented in (Zubair & Abu Mansor, 2018, 2019).

2.7 Part model complexity evaluations

Several methods to evaluate complexity were introduced from past researches and have several interpretations. According to Chase & Murty (2000) complexity can be divided into two types that are design complexity and CAD complexity. The latter introduced CAD complexity evaluation to measure the CAD part model for student's assignment marking. This method is based on CAD embodiment of the design and comparisons were made to part models via its file size, no of objects, instances, and layers. Recently, there are few studies measuring complexity published. Zhang & Thomson (2018) had introduced a knowledge-based measure of product complexity based on Bilinear transformation (BZT) complexity method. Kwon et al. (2016) introduced Feature Shape Complexity (FSC) by quantifying the feature's properties such as edges type, faces type and volume. The quantifications lead to an indexing method so that the part model's complexity value is determined in range below one value. This method is useful to rank feature complexity so that it can be eliminated to reduce part model file size. Part model that has feature such as pattern is said to be higher complexity compare to part model without it. Therefore, it is suggested that to reduce complexity this kind of features can be eliminated.

As far as current literatures, it can be said that there is still no study had been done to assign complexity into machining especially in feature recognitions.

2.8 Multi-objectives optimization solution: Firefly Algorithm

Based on a recent study, there is still room for improving CAPP system in the form of ACAPP to bring it to the next level (Al-Wswasi et al., 2018). In other words, a new approach in selecting the best parameters for a part model from CAD system to be machined is needed. One of the solutions is by considering the use of meta-heuristic algorithm. This metaheuristic algorithm which means higher-level will try to optimize solutions by the combinations of randomization and local search especially in solving a multi-objective problem (Fister et al., 2013a). One of the best meta-heuristic algorithms is the firefly algorithm (FA).

Nature inspired heuristics algorithm is among the popular method in solving multi-objective optimizations problems. To be specific in solving process planning issues in multi-pass turning parameters, past research had shown the development of these algorithm including ant colony optimization (ACO) algorithm (Liu et al., 2013), genetic algorithm (GA) (Dixit, 2007; Mengana & Davim, 2009) , combination of GA and simulated annealed (Saravanan et al., 2003), flower pollination optimization algorithm (FPO) (Xu et al., 2017) and might be the latest is bat algorithm (Chakri et al., 2017).

Despite all the development, FA can still consider as among the best solutions (Fister et al., 2013a). Moreover, the nature of FA is that it is designed for different fireflies to work almost independently, thus making it suitable for parallel implementation. It is proven better than GA and Particle Swarm Optimization (PSO) because FA provides results that aggregate more closely around each optimum (Yang, 2010). FA was first developed by Yang (2010) inspired by the natural behaviour of attractions of firefly behaviour. Since that many works focusing on applications of the FA had been published. Most of them solved optimization problems (Aungkulanon et al., 2011; Belloufi et al., 2014; Carbas, 2016; Johari et al., 2017; Yang, 2009). The FA had been seen to continue to be evolving with many combinations and improvements (Aungkulanon et al., 2011; Fister et al., 2012; Johari et al., 2017; Sayadi et al., 2010; Tesch & Kaczorowska, 2016). Modifications of FA by using quaternion representation

(Fister et al., 2013b) and opposition and dimensional based (Verma et al., 2016) had also been done.

2.9 Cutting tool selections

One of the toughest challenges to begin machining is to select tool. Although there are many tool providers that provide interactive catalogue in selecting the best cutting tool, user has to have a good knowledge of machining to make a good choice. Previous researches had been found in the attempt to automate the process. Arezoo et al. (2000) had developed an expert system called an Expert Computer Aided Tool Selection System (EXCATS) comprising a knowledge base, inference engine, user interface, working database and an explanation facility using Prolog language. Later, a cutting tool selection based on operational and catalogue was developed (Oussama & Hanae, 2015) and machining features were identified from available resources of cutting tool (Chu et al., 2012). Another study implemented an enriched machining feature based towards adaptive cutting tool and machining method selection for small and medium industry (Ji et al., 2018). Moreover, an automated cutting tool selection and cutting tool sequence system was developed by considering more parameters including surface finish, entering angle and geometry analysis (Oral & Cakir, 2004). These developments were helpful in determining the proper cutting inserts especially when optimization was done with the method called Rank Order Clustering. This thesis will adopt principles by (Oral & Cakir, 2004) and apply it to suit volume decomposition feature recognition and the optimization of machining data by using FA.

2.10 Automatic sequencing of machining features.

Decomposed features from CAD model that were defined as SDVs are able to be mapped towards machining features. Specifically, for cylindrical part models, SDVF were classified based on its geometrical face definitions. For example, cylindrical SDVF which decomposed from cylindrical surfaces are related to straight turn and grooving process. Furthermore, machining features such as taper and internal features can also be mapped. To utilize the decomposed features, sequencing processes can be done in order to further organize the system towards manufacturing purposes. Previous studies showed that by sequencing the machining features energy consumption in machining system can be minimized (Hu et al., 2018; Zhang et al., 2016). Moreover, a study focusing on interacting prismatic features had been done by applying knowledge-based and geometric reasoning (Liu & Wang, 2007) and graph-based tolerances (Samuel, 1998). These studies used features' information to generate more information towards machining features in different ways. However, in extracting the feature information, the generation of the SDV can be useful as it can provide the correct info on machining especially on the material removal volume.

2.11 Tool-path planning

In order to produce a workpiece, machining with CNC can reduce production time compare to manual NC machine. Therefore, tool-path codes generation is needed. The advantages of using machining codes or more likely to be called G-codes compare to manual machining or manual parameter insert to the machine control unit (MCU) is complex geometry part model can be machined directly and geometry related problem because of machine CAD incapability can be neglected. This is due to the lack of sketching or drawing function at the MCU during the information transfer from normally 2D drawing to the machine before machining is started.

Related research in recent years shows researchers were focusing on specific problems with specific approaches. Zhao et al. (2007) had developed toolpath optimization for sharp corner pockets, Qu & Stucker (2005) had developed tool–path planning for circular hole based on STL file format. Moreover, relation of tool-path with tool selection had also been done (Chen & Fu, 2011; Somavar Muniappan, 2012). An important aspect in generating the tool-path is the machining feature vertex positions. These positions will determine the position of tool to do the machining processes. Previous research showed that tool-path can be generated by using cloud data point (Masood et al., 2015). These cloud data points were determined from STL CAD file format means for reverse engineering. Furthermore, GA was also been used to generate tool-path for lathe machining (Ramli et al., 2009). GA expressions were used to generate tool-path for flexible transfer line (FTL). Despite the usefulness, the study only considers simple lathe features without considering other machining feature such as groove.

There are variety of machining code available in the industry including Heidenhein, Siemens, Fanuc and others (HelmanCNC, 2016). These controllers control the machining system by using machining codes or G-codes. Although there are arguments the used of G-codes as the name simply because other English alphabets were also used to construct the language. These alphabets can be referred to either in the machining manual for example in DAEWOO (2008), or from numbers of website that provide information for the CNC machining for example in (HelmanCNC, 2016; Warfield, 2018). Nevertheless, "G-codes" is well-known as the common designation of the language and will be used to replace machining codes term throughout this study.

In this thesis, the decomposed SDV are utilized to acquire the vertex point positions. Geometry-base data from the recognized features were embedded with manufacturing feature-based information to generate the tool-path. The effectiveness of the developed algorithm is verified through tool-path simulation at the machine and the production of the part models.

2.12 Related commercial software

One of the most advance software that available in the market is LeanCOST 10 software (“LeanCOST,” 2019). Although this software is functioning to quick and easily estimate the selling cost of a product, this software is more towards Enterprise resource planning (ERP) which are driven towards design for costing (DfC) objectives (Mengonia et al., 2016). This thesis is more related into developing CAPP system in optimizing parameters of turning machining and choosing the best tools. Table 2.1 describe the comparisons of approaches of this thesis and LeanCOST 10 software.

Although most of the time this study is only related into several aspect in LeanCOST 10 software which cover wider aspect in manufacturing, this study can contribute into how optimizing machining parameters can be done in heuristic approach. Furthermore, tooling of the machining and tool-path of the machining can be selected from AFR.

Table 2.1 Comparisons of this study with LeanCOST 10 software

Approaches	**This study**	**LeanCOST 10**
Objective	To optimize turning machining parameters for minimum production cost and tool selection planning.	To simplifies and speeds up the analysis of manufacturing costs.
Function	To bridge between CAD and CAM features by optimizing turning production cost equation using heuristic approach (FA).	It is an ERP software to facilitate different department in manufacturing system.
Feature Recognition approach	This study using volume decomposition method. SDVs are generated and further processes are done from the analysis of these SDVs.	Feature recognition are done from the 3D models and features are identified by surfacing.

2.13 Summary of research gaps

From the literature, it is found that still improvement can be done in the current field. Volume decompositions that currently developed in past literatures shows the extractions in generating SDV for cylindrical part model can still be improved. The motivation can be done by improving the methods previously done by Bok & Abu Mansor (2012) and Kataraki & Abu Mansor (2016) that using translating approach in lofting the recognized faces. To minimize ΔODV values, the way SDV bodies connect to each other can be improved by generating element that can fills the gap and remove overlapping.