



School of Electrical and Mechanical Engineering
Department of Mechanical, Energy and Industrial Engineering

**Development of a CNC machine energy consumption model and
energy analyzer software: Towards energy-efficient CNC machining**

By

Thabang Kablay

ID: 22100057

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Energy in BIUST

Supervisor: Dr. Namoshe

Co-Supervisor: Dr. Setswalo

Faculty of Engineering and Technology

Department of Mechanical and Energy Engineering

namoshem@biust.ac.bw

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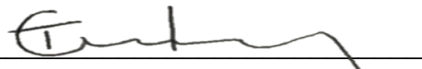
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Candidate: THABANG KABLAY

Student ID: 22100057

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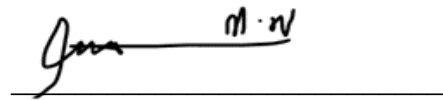
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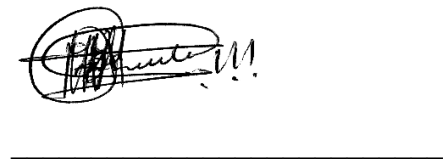
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Dr. Namoshe



Date: 10/09/2025

Dr. Setswalo



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ABSTRACT

This thesis proposes energy-saving strategies for CNC machining to address high energy consumption challenges encountered by manufacturing sectors. A novel energy consumption model for three axis CNC milling machines is presented in this thesis. This energy model computes energy consumption of any three axis CNC machine based on any given numeric code. The model categorizes energy consumption in CNC machining into seven divisions. Each of the seven energy divisions has its own corresponding power state which can be analyzed individually in controlled experiments. An energy analyzer software was developed to compute energy consumption in CNC machining, based on numeric codes. This software utilizes the energy model developed in this thesis to compute energy consumed by CNC machines. The software then selects the most energy efficient tool pathway strategy. By conducting some machining trials, the energy model and software were validated. The greatest percentage deviation of the software predictions from the measured energy consumption was -1.9%. Nine tool pathway strategies were studied in this thesis using energy analyzer software. The energy consumption of the nine tool pathway strategies was studied on two geometries, the rectangular pocket and the circular pocket. Results from the software revealed the pocket-in and the pocket-out tool pathway strategies were the most energy efficient tool pathways for both the rectangular pocket and the circular pocket. Spiral-in tool pathway had the highest energy demand in rectangular pockets while zig-y tool pathway strategy had the highest energy demand in circular pockets. Results from the software also revealed that, energy efficiency of different tool pathway strategies vary with respect to the geometry being machined. Energy savings were up to 67% for rectangular pockets and up to 33% for circular pockets.

Keywords: CNC machine, NC codes, tool pathways, energy efficiency, Energy prediction software, energy model.

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List of abbreviations

CAD	Computer aided design
CAM	Computer aided manufacturing
CNC	Computer numerical control
G-code	Preparatory functions code
GUI	Graphical user interface
M-code	Miscellaneous functions code
MRR	Material removal rate
NC	Numeric code
SEC	Specific energy consumption

Nomenclature

E_{total}	Total energy consumed by the CNC machine
E_{block}	Total energy consumed by each block of NC
E_{fixed}	Energy consumption for just keeping the machine on
$E_{coolant_pump}$	Energy consumption of the coolant pump
$E_{spindle}$	Energy consumption for spindle rotation
E_{rapid}	Energy consumption for movement of the feed axis during rapid motion
E_{linear_int}	Energy consumption for linear interpolation cutting
$E_{circular_int}$	Energy consumption for circular interpolation cutting
E_{tool_change}	Energy consumption for tool change process
E_{feed_cx}	Total energy consumption for moving the feed drive system in the x-axis direction during circular interpolation
E_{cut_cx}	Energy consumption for cutting in the x-axis direction during circular interpolation
P_{fixed}	Mean power consumption for just keeping the machine on
$P_{coolant_pump}$	Mean power consumption of the coolant pump
$P_{spindle}$	Mean power consumption for spindle rotation
P_{feed}	Mean power consumption of the feed drive system
P_{linear_cut}	Mean power consumption for material removal along the specified axis
$P_{circular_feed}$	Mean power consumption for movement of the feed drive system during circular interpolation
$P_{circular_cut}$	Mean power consumption for material removal during circular interpolation

P_{feed_cx}	Power consumption for moving the feed drive system in the x-axis direction during circular interpolation, respectively
$P_{mfeed_cx}, P_{mfeed_cy}$	Mean power consumption for moving the feed drive system in the x-axis direction and y-axis direction during circular interpolation, respectively
P_{cut_cx}	Power consumption for cutting along the x-axis direction during circular interpolation
P_{mcut_cx}, P_{mcut_cy}	Mean power consumption for cutting in the x-axis direction and y-axis during circular interpolation, respectively
$P_{circular_feed}$	Mean power consumption for movement of the feed drive system during circular interpolation
$P_{circular_cut}$	Mean power consumption for material removal during circular interpolation
$P_{tool_magazine}$	Power consumption of the tool magazine actuation system
P_{block}	Power to be consumed by a block of NC
$P_x(t), P_y(t)$	Power consumption values at a given time t , for machining in the x-axis and y-axis directions, respectively
t_{state}	Time duration of a given power state
t_{fixed}	Time duration for the fixed power state
$t_{coolant_pump}$	Time duration for the coolant pump power state
$t_{spindle}$	Time duration for the spindle rotation power state
t_{feed}	Time duration for the feed drive system power state
t_a	Time taken during the acceleration phase of feed system
t_{linear_cut}	Time duration for material removal power state

$t_{circular_feed}$	Time duration for movement of the feed drive system during circular interpolation
$t_{circular_cut}$	Time duration for material removal during circular interpolation
$t_{circular_int}$	Time taken to complete the circular interpolation
t	Time taken to complete a given circular interpolation
$t_{tool_magazine}$	Time duration for which the tool magazine actuations system is activated
t_{block}	Time duration for a give block of NC
N	Spindle rotational speed
m, k	Constants for spindle rotation power consumption
$a_i, b_i, c_i, q_i, u_i, s_i$	Machine specific constants
$a_x, b_x, c_x, q_x, u_x, s_x$	Constants for x-axis direction
$a_y, b_y, c_y, q_y, u_y, s_y$	Constants for y-axis direction
$a_z, b_z, c_z, q_z,$	Constants for positive z-axis direction
$a_{-z}, b_{-z}, c_{-z}, q_{-z},$ u_{-z}, s_{-z}	Constants for negative z-axis direction
f	Feedrate
W	Weight of the work piece
MRR_i	Material removal rate in a specified axis
f_i	Feedrate in a given axis
f_x, f_y, f_z	Feedrate in the x-axis, y-axis and z-axis directions respectively
x_1, y_1, z_1	Coordinates for the starting point of cutting tool

x_2, y_2, z_2	Coordinates for the end point of the cutting tool
x_d, y_d, z_d	Distances moved in the x-axis, y-axis and z-axis respectively
d	Straight-line distance between point 1 and point 2
d_a	Distance moved by the feed axis during the acceleration phase of feed System
D	Diameter of the cutting tool
w	Width of cut
d_c	Depth of cut
l	Length of the circular interpolation arc
R	Radius of the circular interpolation arc
θ	Circular interpolation angle
θ_1, θ_2	Starting angle of circular interpolation and final angle of circular interpolation, respectively
θ'_2	Intermediary angle in circular interpolation
I, J	Displacements to the center of the circular interpolation arc, in the x-axis and y-axis directions respectively
x_r, y_r	Coordinates of the reference point
l_1	Distance between reference point and point 1
l_2	Distance between reference point and point 2

Chapter 1: INTRODUCTION

1.1 Introduction

Computer Numerical Control (CNC) machines play a pivotal role in modern manufacturing processes, enabling precision and accuracy at a faster rate. Industries now depend greatly on automated production because through automation it is possible to produce more high-quality standardized products rapidly (Javied et al., 2016; Soori et al., 2024). A study carried out in 2023 revealed that electric drives, which power CNC machines and other industrial systems, account for over 65% of total energy consumption in advanced manufacturing industries, directly linking automated production to rising carbon footprints (Soori et al., 2023). High energy consumption in mechanical machining can be attributed to high carbon emissions and an increase in manufacturing costs (Shokrani et al., 2024; Zheng et al., 2024). Mori et al. (2011) stated that most manufacturing machine tools in industries are powered by electric energy. Electricity is mainly generated from fossil fuels around the world (Hudedmani et al., 2016). Hudedmani et al. (2016) further stated that generating electricity from fossil fuels has negative environmental effects as it leads to climate change and also results in various health risks to humans and other animals.

Due to recent acceleration of global warming, countries around the world have begun to implement carbon tax and carbon labeling policies, to cope with the growing greenhouse effect and reduce machine tool products carbon footprint (Foumani & Smith-Miles, 2019; Q. Liu et al., 2017; World Nuclear Association, 2024). According to U.S Environmental Protection Agency (2024), more than 30% of carbon emissions are produced by the manufacturing industry, as shown in Figure 1. 1. Studies by Zhou et al. (2016) revealed that energy consumption in industry is increasing rapidly. In 2022, studies carried out showed that around 35% of world energy consumption is consumed by the industrial sector (U.S. Energy Information Administration, 2023). Being one of the main sources of carbon emissions, the manufacturing industry has recently faced pressures from environmental impact and economic impact groups, urging the manufacturing sector to enforce low-carbon manufacturing strategy (Cai et al., 2019; Giampieri et al., 2019). This has also resulted in more strict guidelines, such as the greenhouse gas protocol (World Resource Institute, 2024). In August 2013 the State Council said that China, the largest contributor to carbon emissions, should reduce its carbon emissions by 40-45% by 2020 (World Nuclear Association, 2024). During the Paris climate change conference in December 2015, China announced that it intends to reduce carbon dioxide emissions by 60-65% from 2005 levels, by 2030 (World Nuclear Association, 2024). It will therefore be of great importance to look into developing energy saving strategies to achieve sustainable manufacturing.

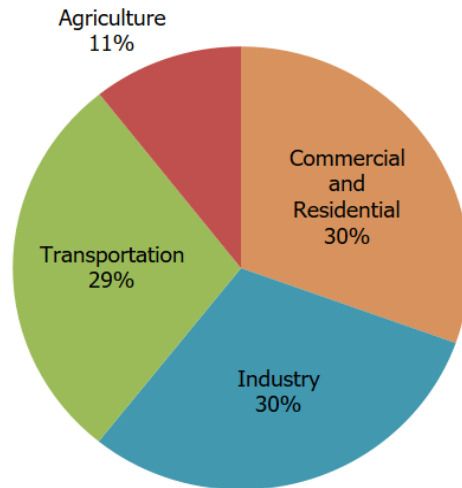


Figure 1. 1: Total U.S. Greenhouse Gas Emissions by Economic Sector (U.S Environmental Protection Agency, 2024)

Various researches have revealed that manufacturing industries have consumed about one-third of the total energy on earth (Cai, Wang, et al., 2022). It is therefore important for manufacturing industries to undertake effective measures to reduce energy consumption and carbon dioxide emissions in order to contribute to the global target for carbon neutrality (Cai, Li, et al., 2022). Currently, the rate of effective energy utilization in machining is usually less than 30% (Sihag & Sangwan, 2020). Garwood et al. (2018) stated that improving the efficiency in machining has become increasingly important due to increasing energy costs and environmental concerns. This calls for more studies and research to be carried out in the area of improving energy efficiency in mechanical machining. In recent years, different approaches of energy-efficient machining processes have been investigated, ranging from machining parameter optimization, numeric code (NC) optimization, scheduling optimization, etc. These will be discussed in more detail in Chapter 2.

This research is primarily aimed at reducing energy consumption in CNC machining by selecting energy efficient tool pathway strategies for machining. To achieve this, an energy model for predicting energy consumption in CNC machining was developed. This energy model was then used to develop a software which predicts energy to be consumed by given NC programs. From the energy results presented by the software, energy efficient tool pathway strategies were determined.

1.2 Background information

CNC machines are advanced machining tools used for precision cutting and shaping of various materials. They are pivotal tools in modern manufacturing, engineering, and prototyping industries

(Javied et al., 2016). They represent a cornerstone technology in the realm of computerized manufacturing, enabling precise and accurate automated fabrication of complex parts and components from various materials. CNC milling machines find applications across various industries, including automotive, aerospace, medical, and consumer electronics. They are used to produce a wide range of parts, such as engine components, aircraft structures, surgical implants, molds and consumer electronics housings (Xometry, 2022). These machines are versatile, capable of machining different materials like metals, plastics, wood, and composites (Xometry, 2022). Among the different types of CNC milling machines, the three axis CNC milling machine, shown in Figure 1. 2, Figure 1. 3 and Figure 1. 4, is a fundamental and widely used variant (Ye, 2023).

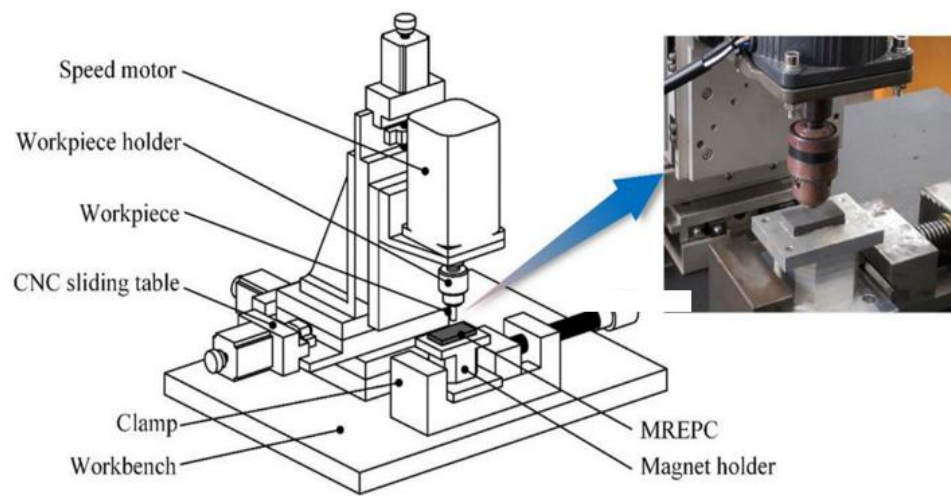


Figure 1. 2: Labeled schematic of a CNC machine (Xu et al., 2019)

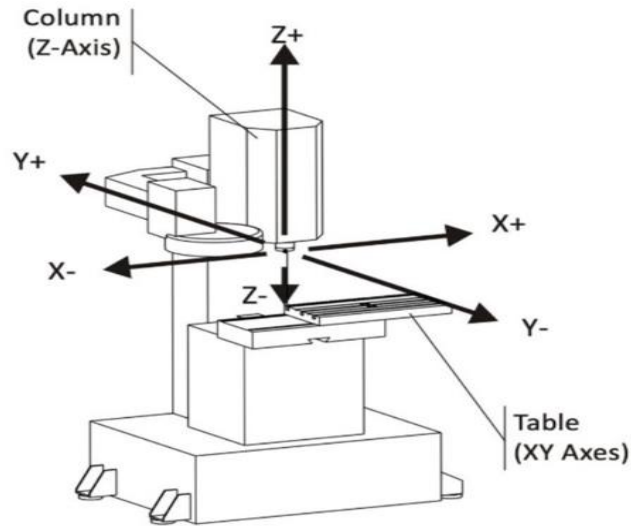


Figure 1. 3: Schematic of a CNC machine with labeled coordinate system (Samala & Amanda, 2023)

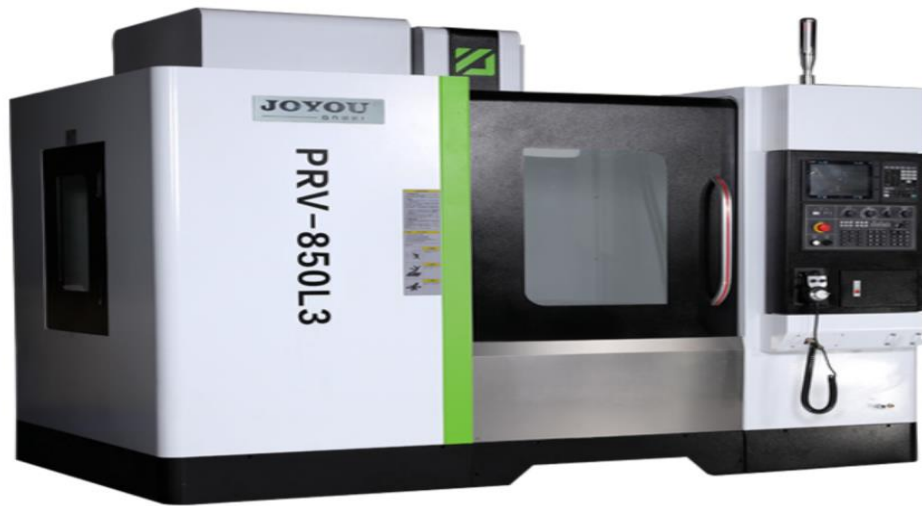


Figure 1. 4: CNC machine used in industries (Megan, 2018)

A three axis CNC milling machine operates based on the Cartesian coordinate system. Movement of the cutting tool relative to the work piece, is in the x, y and z axes directions. Components of three axis CNC machines include; Frame, which provides structural support and rigidity to withstand machining forces; Spindle, which holds the cutting tool and rotates at high speeds to remove material from the workpiece; Feed axis System, which consists of linear guides, ball screws, and motors to facilitate precise movement along each axis; Control System, which includes

a computer, controller, and software to program and execute machining operations; Worktable, which supports the workpiece and can move along the x and y axes; Automatic tool Changer, which automatically changes tools, enabling continuous machining without manual intervention (Ye, 2023).

The process of operating CNC machines usually begins with the creation of a 3D model using Computer Aided Design (CAD) software. The design is then translated into machine-readable code using Computer Aided Manufacturing (CAM) software. CAM software automates the process of generating toolpaths based on CAD models, eliminating the need for manual programming. Some of the CAM software widely used for CNC machine programming are Mastercam, Solidworks, Autodesk Fusion 360, and Siemens NX CAM (Axsom, 2022).

CAM software generates toolpaths based on the design, specifying the tool's movement in the x, y, and z axes directions. Toolpath generation involves determining the sequence of movements that the cutting tool will follow to machine the desired part geometry. The toolpaths are converted into numeric codes (NCs), also known as G and M codes. These are a set of instructions that the CNC milling machine understands. M-code (Miscellaneous functions code) commands are used for auxiliary functions such as tool changes, coolant control, and spindle control. G-code (Geometric code) guides the machine's movements and controls the cutting tool's operations. The workpiece is securely mounted on the table. The CNC milling machine executes the programmed toolpaths, cutting away material to achieve the desired shape. CAM programs offer advanced features such as toolpath optimization, collision detection and simulation. NC editors provide a platform for manually developing, editing, and debugging NC programs (Axsom, 2022).

CNC machines can be programmed manually. Manual programming involves directly typing G and M codes to the control unit editor, to specify tool movements, speeds, feeds, and other parameters. This method requires a deep understanding of NC syntax and machining principles but provides complete control over the machining process (Xometry, 2022). Table 1.1 shows some of the commonly used G and M codes.

Table 1. 1: commonly use G and M codes (TIE Industrial Fanucworld, 2024)

NC code	Machine instruction
G00	Moves the tool in rapid travel
G01	Moves the tool using a set feedrate
G02	Moves the tool along a clockwise arc path
G03	Moves the tool along a counter-clockwise path
G40	Cancel cutter compensation
G41	Cutter compensation left
G42	Cutter compensation right
G43	Tool length compensation positive
G44	Tool length compensation negative
G49	Tool length compensation negative
G90	Absolute measurements
G91	Incremental measurements
M03	Spindle on Clockwise
M04	Spindle on Counter-clockwise
M05	Spindle stop
M06	Tool change
M08	Coolant on
M09	Coolant off
M30	End of program and rewind to beginning of program

High energy consumption in manufacturing processes, particularly in CNC machines, is of significant concern due to its environmental impact, operational costs, and sustainability considerations (Hudedmani et al., 2016). Understanding factors influencing energy usage in CNC machines is crucial for optimizing efficiency and minimizing resource utilization (Garwood et al., 2018).

A number of researchers have studied energy consumption in CNC machining with the aim of reducing energy consumption in CNC machines. Studies carried out by various researchers have revealed that factors affecting energy consumption in CNC machines are;

- **Machine Design:** The design of CNC machines greatly influences their energy consumption. Modern machines often incorporate energy-efficient components and technologies, such as servo motors, regenerative braking systems and variable frequency drives to reduce power requirements during operation. (I. Edem, 2016; S. S. Pavanaskar, 2014; Sihag & Sangwan, 2020)
- **Spindle and Cutting Tools:** The efficiency of the spindle motor and cutting tools significantly impacts energy consumption. High-speed spindle rotation and optimized tool geometries can minimize cutting forces and reduce the power needed to remove material from the workpiece. (Campatelli, Lorenzini, et al., 2014; I. F. Edem & Balogun, 2018)
- **Material and Workpiece Characteristics:** The type of material being machined and the complexity of the workpiece affect energy consumption. Machining harder materials or producing intricate geometries may require higher cutting forces, leading to increased energy usage. (Li et al., 2013)
- **Toolpath Optimization:** Efficient toolpath planning and optimization can minimize unnecessary movements and reduce idle time, resulting in lower energy consumption. CAM software plays a crucial role in generating different toolpaths required for machining. (I. F. Edem et al., 2019; S. S. Pavanaskar, 2014)
- **Cutting Parameters and feedrate:** Proper selection of cutting parameters, such as spindle speed, feedrate, and depth of cut can optimize material removal rates while minimizing energy consumption. Machining at lower speeds and feedrates reduces power demand and prolongs tool life. (Campatelli, Lorenzini, et al., 2014; Diaz et al., 2011; Mori et al., 2011)
- **Coolant and Lubrication Systems:** Coolant and lubrication systems are essential for maintaining tool life and achieving quality surface finishes. However, excessive coolant usage can contribute to energy consumption. Using minimal lubrication techniques or implementing efficient coolant recycling systems can help reduce energy usage associated with coolant management. (I. Edem, 2016; S. S. Pavanaskar, 2014)

- Machine Utilization and Downtime: Maximizing machine utilization and minimizing downtime are critical for energy efficiency. Idle machines consume energy without contributing to production output. Implementing predictive maintenance strategies and scheduling jobs efficiently can optimize machine utilization and reduce idle energy consumption. (I. Edem, 2016; Sarıkaya et al., 2022; Sihag & Sangwan, 2020)

A number of researchers have worked on developing strategies for reducing energy consumption in CNC machining. Energy consumption in CNC machines is a multifaceted issue influenced by various factors ranging from machine design and cutting parameters to material selection and coolant usage. By adopting a holistic approach to energy management, manufacturers can optimize CNC machining processes for efficiency, sustainability, and cost-effectiveness while maintaining high levels of productivity and quality. Continuous monitoring, measurement and implementation of optimization strategies are essential for achieving energy savings and improving overall manufacturing performance. The work presented in this thesis focuses on reducing energy consumption in CNC machining with the focus being on tool pathway strategies. Tool pathway strategies are carefully studied to observe how they consume energy in CNC machining.

1.3 Statement of the problem

CNC machines consume a large amount of electric energy, which increases machining cost (Garwood et al., 2018; Javied et al., 2016; Sihag & Sangwan, 2020). Besides increasing machining costs, high consumption of electric energy in CNC machines have negative impacts on the environment as most electric energy is produced from fossil fuels (Cai, Li, et al., 2022; Hudedmani et al., 2016). This was further supported by the World Nuclear Association (2024), which revealed that in China, 69% of electric energy is produced from fossil fuels, predominantly coal. Hudedmani et al. (2016) stated that burning fossil fuels is a health hazard to humans and animals, and it also leads to global warming.

1.4 Objectives

The overall objective of this study is to reduce energy consumption in CNC milling machines, by using energy efficient tool pathway strategies for machining. The specific objectives are:

- To develop an energy consumption model for CNC machines.
- To empirically determine model constants for a specified CNC machine
- To develop a software for computing energy consumption in CNC machines
- To analyze energy consumption of different tool pathway strategies in a specified CNC machine

1.5 Thesis organization

Chapter 1 is the introduction of this thesis. It introduced the thesis, states problems which prompted this research and gives objectives which are to be achieved by this thesis. Chapter 2 is the literature review for this thesis. It reveals what has been done by other researchers with regard to the work carried out in this thesis. Chapter 3 is the methodology of this thesis. It outlines procedures which were carried out to achieve objectives of this thesis. Chapter 4 deals with the CNC energy consumption model proposed in this thesis. It reveals in detail how the energy consumption model was developed. Chapter 5 presents the design of the CNC energy analyzer software. This software utilizes the CNC energy consumption model to select the most energy efficient tool pathway strategy for CNC machining. In chapter 7, the energy analyzer software and the CNC energy consumption model are validated. Still in chapter 7, tools pathways strategies are analyzed with respect to energy consumption in CNC machining. Chapter 8 is the conclusion for the thesis, it gives a summary of results obtained in this thesis. Chapter 8 also presents research areas for future work related to the work presented in this thesis.

Chapter 2: LITERATURE REVIEW

2.1 Introduction

Number of researches have been carried out with the aim of improving energy efficiency in CNC machining. In this chapter, a review of literature related to modelling of energy consumption in CNC machining and optimization of energy consumption with respect to tool pathways will be presented.

2.2 Energy consumption models of CNC machines

Zhou et al. (2021) stated that modeling energy consumption of CNC machines is a prerequisite for manufacturers to save energy, reduce environmental pollution and increase profits. They stated that this will be of great significance to the healthy development of the manufacturing sector. Some of the energy models discussed in this section are summarized in Table 2. 1.

Avram & Xirouchakis (2011) developed an energy model which estimates the energy demand of the spindle and feed axes with respect to 2.5-dimension milling strategies. Their model, shown in Table 2. 1, considered steady-state and transient regimes. In their study, the specific amount of fixed energy drawn by a machine was determined. They went on to develop a software that extracts machining parameters such as spindle speed and feedrate from the NC code to evaluate the value for the energy consumption. Building on the work of Avram & Xirouchakis (2011), Diaz et al. (2011) studied energy consumption in CNC machining by varying machining parameters for cutting width and cutting depth, resulting in a model of energy consumption based on variable material removal rate. In the same year, Mori et al. (2011) conducted experiments which showed strong correlation between specific energy consumption and material removal rate. They went on to develop an energy model based on the strong correlation between specific energy consumption and material removal rate. They further went on to conduct experiments with varying machining parameters (feedrate, cutting speed, etc.) and concluded that the maximum allowable values of machining parameters proved to be the most suitable combination for optimizing energy consumption. Still in 2011, Kong et al. (2011) studied the effects of different tool pathway machining strategies in the production of identical parts and concluded that energy consumption is different when the same part is manufactured using different tool pathways. The following year, He et al. (2012) studied the relationship between NCs and energy-consuming components of CNC machines. Parameters were extracted from NCs to evaluate energy consumption during machining.

Balogun & Mativenga (2013) proposed an energy demand model for machining toolpaths using the energy states of the machine tool. They used the following energy states in modeling energy demand of the machine tool; the basic energy state, which is energy consumed by the supporting systems to operation of the machine tool. It includes the energy consumed by the computer units, lighting, cooling fans etc.; the ready energy state, which includes energy consumption for

operation of other machine tool processes excluding energy consumed by the cutting process; The cutting energy consumption, which is the energy consumed for material removal and the coolant system. They stated that the main energy consumers in machine tools consist of; the auxiliary units, which includes fans, unloaded servo motors, lighting, computers, air pumps, coolant pumps, lubrication pumps etc.; spindle rotation; feed axes system; and the tool change system. They further stated that the operation of these components during machining is given by NCs. Therefore, the prediction of energy demand in machining could be obtained by relating the energy consuming components with NCs. This is critical for determining the influence of NCs and the effects of linear and circular interpolations on the power and energy required during mechanical machining.

Li et al. (2013) further studied how different machining parameters affects energy consumption in CNC machining. They concluded that energy consumption depends on constant factors and variable factors. Constant factors were considered to be; energy consumption of the machine tool in standby mode, energy consumption for tool change, number of tool changes required and energy consumption of the coolant system. Variable factors were considered to be; energy consumption for the spindle drive which depends on the spindle speed, energy consumption for feed axis movement which depends on feedrate and energy consumption for material removal which depends on the material removal rate, the material being machined and tool wear.

Jia et al. (2014) introduced Therblig-based energy supply modeling of CNC machine tools to compute energy consumption in operation of the CNC machine. The Therbligs include energy consumed by standby operation, lighting, spindle rotation, feed axes system, coolant system, tool changing and cutting process. Building on Jia et al. (2014)'s work on therblig-based energy supply model, Lv et al. (2014) developed therblig power models for calculating the energy supply for CNC machine tools using machining process parameters. In modelling the power consumption for each Therblig, the machine tool design and operating parameters were taken into account.

Borgia et al. (2014) developed a reduced model for the analysis of energy consumption of a machine tool during face milling operations. The model is made up of significant parameters detailing the workpiece, the machining process and the machine tool. A machine learning model was trained based on the machine tool feed motion and cutting operations. Aramcharoen & Mativenga (2014) designed a machining parameter-based energy model, in which power states for estimating energy demand of a machine tool system were analyzed to optimize energy consumption. Campatelli et al. (2014) conducted experiments to evaluate and optimize machining parameters in order to minimize the power consumption in a milling process performed on a CNC machine. The parameters evaluated were the cutting speed, the axial and radial depth of cut, and the feedrate. The experimental results were analyzed using a response surface method in order to obtain a suitable model for the fine tuning of the process parameters. They concluded that, to obtain a lower environmental footprint it is necessary to maximize the material removal rate by selecting cutting speed, feedrate, and chip section that are as large as possible but within the allowable working conditions of the cutting tool. Campatelli, Scippa, et al. (2014) investigated strategies for optimizing energy efficiency and reducing environmental impacts due to the CNC machining

process. They studied energy consumption for machining along the x-axis and y-axis. They concluded that machining along the y-axis consumed more power than machining along the x-axis.

Pavanaskar & McMains (2015) developed an analytical energy consumption model, shown in for CNC machining with the emphasis on the geometric aspects of toolpaths and the material removal rate. They performed several controlled machining experiments to isolate, identify, and analyze the effects of various aspects of toolpaths, such as path parameters and angular change, on energy consumption. They went on to develop a web-based software interface for their model, that, once customized for a particular CNC machine, computes energy demand for a toolpath given its NC. In validating the energy model and software, they recorded a deviation between -6% and 5%. Pavanaskar et al (2015) also conducted a study to develop energy efficient tool paths based on selectively relaxed vector fields. These tool paths proved to be more energy efficient than those found in MasteCAM software. Liu et al. (2015) evaluated energy consumption activities based on the main driving unit of a machine tool system recognizing the start-up, idle, air-cutting and the material removal energy consumption. N. Liu et al. (2015) developed a model for energy consumption prediction in machining processes and validated the model in experiments. Using the established cutting force model, cutting power at the tool tip was obtained analytically. The relationship between total power consumed by the machine tool and cutting power at the tool tip was characterized empirically. By considering cutting power at the tool tip, their model could reflect the effect of material removal rate on energy consumption and had better prediction accuracy than the previous models which they had considered.

In 2016, Sealy et al. (2016) studied the relationships between cutting parameters, tool wear, and energy consumption in CNC milling machines. Using data from experiments, a regressive model was developed to reflect the specific energy required for material removal. Altıntaş et al. (2016) developed a model for estimating the energy demand for a CNC milling machine. The Energy model was optimized for different cutting parameters for milling operations. In validating the model, the highest deviation recorded was 5%. Building upon the work by Balogun & Mativenga (2013), Balogun et al. (2016) developed and e-smart software to validate the energy model by Balogun and Mativenga (2013). The absolute deviation of the e-smart software from experimental results was 12%.

Ma et al. (2017) developed a specific energy calculation model and an optimization model to predict and optimize energy consumed by a CNC milling machine. In their model, the impacts of cutting parameters on energy consumption were fully considered and the MATLAB optimization toolbox was used to evaluate energy demands. The predictive accuracy of the energy model was greater than 90%, for all cases studies considered. Zhou et al. (2017) conducted experiments to study the relationships between specific energy consumption and; spindle rotation speed, cutting parameters, material removal rate, air cutting power, and material removal power. They developed an energy model in which cutting parameters or material removal rate were regarded as independent variable. Their model demonstrates better fitting correlation when compared with

previous models and increased the accuracy of predicting machining energy in the milling process. Cutting parameters or material removal rate were regarded as independent variable in those models.

Working on improving the effectiveness of past models, Edem & Mativenga (2017) developed a feed axes energy demand model, which incorporates the weights of feed axes, machine vice, and workpiece. They went on to develop a software based on their model. This software predicted energy to be consumed by a CNC machine during machining and machining time. Results from their work revealed that, shorter linear path lengths and circular path segments were highly energy intensive. They stated that this was due to the fact that the maximum feedrate may not be reached due to constraints imposed by acceleration and deceleration. Edem & Mativenga (2017a) went on to study effects of machine tool vice orientation on energy consumption in CNC machining. The study was performed using the Takisawa Mac-V3 milling machine. They observed that energy consumption is at a minimum, when the machine tool vice orientation is at 0° , that is, when cutting is along the x-axis. They further stated that, when the orientation was between 15° and 75° the energy consumption was higher than when the orientation was at 0° and 90° . Their studies also showed using the most energy efficient orientation resulted in the least surface roughness. They concluded that machining with machine tool vice oriented at 0° may save up to 29% in electrical energy irrespective of feedrates considered.

Zhao et al. (2017) studied how different components of machine tools consume energy, with the aim of developing energy efficient strategies. They classified machine tool energy states into three levels; cutting specific energy, spindle specific energy, and basic machine specific energy. With the aim of reducing energy consumption in machine tools, Zhao et al. (2018) conducted experiments to determine machining parameters which give both minimal surface roughness and minimal energy consumption in machine tools. The machining parameters considered were cutting depth, cutting width, feedrate and spindle speed. They developed machine tool specific energy consumption model, based on material removal rate. To minimize machine tool specific energy consumption and surface roughness, they employed the grey correlation analysis method to optimize machining parameters.

Triebe et al. (2018) developed a machine tool energy model, identifying energy consumption by main components of a representative machine tool. They gave a major focus to motors since they account for a large portion of the total energy consumption. To better understand the energy flow and energy consumption of machine tools, they developed an energy flow map which made it easy to identify the relative energy consumption features of a machine tool. Imani Asrai et al. (2018) developed a mechanistic model for the consumption of energy in milling processes, analyzing the milling machine as a thermodynamic system. The model was validated and all the deviations recoded were less than 1%. Luan et al. (2018) studied energy consumption in machining process in relation the effects of tool pathways. They developed energy consumption model that included the effects of tool paths. In validating the model, six milling tool paths were used to machine workpieces, thereafter surface integrity of the machined surface was evaluated using X-ray

diffraction and optical surface profiler. The optimization of the tool pathways was shown to offer significant opportunities in reducing energy consumption by up to 50% during the machining process. They concluded that optimization in the machining process can be achieved by balancing the tradeoffs between machining time, cutting power, and surface integrity. The model was validated and all the deviations recorded were less than 1%.

Li et al. (2019) stated that energy consumption modeling of automatic tool change processes is a method that has been overlooked in previous investigations, when modeling CNC machine energy demand. They revealed that tool change energy and time, vary with respect to the turret motor rotation angle for changing tools. energy consumption model for automatic tool change processes can be integrated into the overall energy consumption estimation model as a whole. They concluded that this approach improves the accuracy of the previous existing models. Camposeco-Negrete & de Dios Calderón-Nájera (2019) conducted an experimental study to optimize the energy consumption during slot milling of aluminum alloy 6061. They selected surface roughness and specific energy as key characteristics of the milling process. Results obtained showed that the approach presented in their work allowed for a reduction of energy consumption by up to 31.57%. They were also able to significantly reduce the surface roughness by up to 65.35%. The impacts on the environment related to the milling process were reduced without compromising the performance and quality of the final product. Shi et al. (2019) developed a cutting power-based energy consumption model for milling process. The model consists of an idle state that is a function of rotation speed, and an additional state that is proportional to the cutting power at the tool tip. The model has the capability to predict energy consumption in both slotting and partial-immersion milling. They stated that, compared with previous models in literature, the proposed model was more accurate and more reliable for predicting energy consumption in milling experiments.

Energy consumption in CNC machining can be divided into two categories, the main unit and the auxiliary unit (Denkena et al., 2020). The main unit is responsible for providing energy for the movement of the feed axis, rotation of the spindle and for material removal. The auxiliary unit include the other energy consuming operations required by the machine tool. These includes, the coolant system, fan system and other supporting systems depending on the machine tool. Han et al. (2020) conducted several experiments to study how trade-offs between cutting power and material removal rate can be used to improve energy efficiency in CNC machining. They used the grey correlation analysis to weigh the two parameters. The linear decreasing particle swarm optimization algorithm was utilized to solve the model. Several case studies were conducted to validate the model. The case studies also showed that the model was effective in optimizing energy efficiency.

Zhou et al. (2020) developed a multi-objective optimization model with the aim of low-carbon-oriented integrated optimization of cutting parameters and tool paths for cavity milling. Their model takes processing time, carbon emissions and processing cost as its objectives. A two-layer interactive solution was adopted to solve the model, which first utilizes non-dominated sorting genetic algorithm-II for upper layer optimization of cutting parameters, and then takes its results

as the input for under layer optimization of tool paths using an improved genetic algorithm. Experimental results revealed that their approach could reduce the indicators of low-carbon manufacturing and lead to a 20.71% decrease of processing time, 15.38% decrease of carbon emissions and 14.28% decrease of processing costs. Y. Zhang et al. (2020) studied how different cutting parameters affect energy consumption in CNC machining. They developed energy consumption prediction model by classifying the energy consumption in CNC machining into different categories. Experimenting with individual cutting parameters they showed that significant energy saving could be achieved by using optimal cutting parameters for minimum energy consumption. They recommended that further studies should be conducted to explore how integrating all the cutting parameter into a single study could lead to further energy savings. X. Zhang et al. (2020) developed an analytical energy consumption model aimed at optimization of cutting parameters. The model took into account tool wear considering nonlinearities caused by tool run-out and the trochoidal trajectories of cutting edge. Milling experiments were performed to validate the accuracy of the proposed energy consumption model along with the optimization method. The optimization method based on the energy model was able to reduce the energy consumption by 7.89% compared with the empirical selection method.

Pawar et al. (2021) developed an energy model for circular geometries. The model is developed based on process and geometry. The developed model can be used for estimating the power consumption for milling of circular geometries without conducting the costly experiments. Brillinger et al. (2021) developed a machine learning based approach for predicting energy consumption based on the NC code of the part to be produced. A number of models were investigated and the highest deviation recorded was 7.16%. Pawanr et al. (2021) developed an energy model for machine tools which accounts for both the steady energy state and the transient energy state. They stated that the transient energy state tends to be neglected by researchers, as its profile is stochastic and its time duration is concise, which led to less accurate models. They revealed that this approach gives more accurate prediction of energy consumption in machine tools.

Feng et al. (2021) proposes an energy prediction model taking into account power consumption in standby state, spindle rotation in non-load, rapid movement in x, y and z directions, and specific energy consumption (SEC) in the x and y cutting directions, respectively. The method was validated by 27 trial cutting experiments in the VMC850E machine and the results show that the SEC in the x and y cutting directions is different. The correlation coefficient of the improved SEC model was more than 99.98% in each segment. Moreover, it was observed that spindle power should be represented as piecewise linear representation according to spindle speed characteristic. Zhou et al. (2021) developed an energy model which is suitable for machining multiple materials, by combining the empirical and theoretical model analysis. Key variables that affect the energy consumption in cutting status were determined. The proposed model improved applicability and accuracy to existing empirical models.

Pawar et al. (2022) took an approach of combining analytical models for the cutting power and empirical models for the idle speed and auxiliaries, to model the energy demand of curved geometries. Using this approach, an error of less than 2.27% was achieved. Shi et al. (2022) developed an approach for indirect evaluation of cutting force coefficients, which enable previously developed energy models to accommodate multiple workpiece materials. By using a pre-calibrated energy model, this approach was used to determine cutting force coefficients of new materials based on measured power consumption. The simulated annealing algorithm was developed to search for the cutting force coefficients. The cutting force coefficients obtained, achieved high accuracy for power consumption predictions and instantaneous cutting force evaluation.

Cheng et al. (2022) developed an estimation methodology for energy consumption based on STEP-NC program, to compute energy consumption during machining. This methodology is capable of integrating the STEP-NC data model with the energy consumption model. They stated that all the information needed for the estimation of energy consumption comes from the STEP-NC program. Factors influencing energy consumption were analyzed in detail and the energy consumption with regard to the STEP-NC program was measured through machining experiments. Energy consumption estimation methodology based on the machining feature was constructed, and the mapping relationship between STEP-NC program and the estimation method was established. The energy consumption estimation framework, with the STEP-NC program as input, was then developed. This framework was validated by practical machining experiments, and had estimation accuracy of more than 90% in all experiments. Zhao et al. (2022) developed theoretical models to illustrate the evolution of the material removal energy, material removal rate, specific cutting energy and stresses. They conducted experiments with different cutting parameters and surface morphologies. They also experimented with and analyzed cutting forces. Experimental Results revealed that the total material removal energy decreases with the increasing of feedrate, but the maximum material removal energy increases by about 90.67% and 6.25% when the feedrate increases from 1 $\mu\text{m}/\text{rev}$ to 2 $\mu\text{m}/\text{rev}$ and from 2 $\mu\text{m}/\text{rev}$ to 3 $\mu\text{m}/\text{rev}$, respectively. They went on to reveal that, despite high cutting energy required per time at large feedrate, the total net material removal energy reduces with the increase of feedrates. They concluded that, energy could be saved by adopting large feedrates, however, surface finish is one factor being compromised at large feedrates.

Feng et al. (2023) developed tools for energy consumption optimization, based on NC codes. They developed an energy model based on detailed analysis of energy consumption activities in the machining processes. They went on further to design an optimization algorithm hybridizing the genetic algorithm and the ant colony algorithm to minimize air-cutting toolpaths to optimize the energy model. Two case studies were conducted to validate the approach which they presented. The two case studies revealed that the accuracy of the energy model was 95.3% of the measured energy consumption. These studies also showed that, based on the optimized energy model, the total length of air-cutting toolpaths was reduced by 43.8%, and the total machining time was also

reduced by 25.8%. The energy consumption during the air-cutting process was reduced by 43.8%. Results from their study proved that the developed methodology can achieve substantial energy-savings for machining processes.

Brillinger et al. (2023) presented a workflow and a method for predicting energy demand for machining components. This energy demand prediction is performed during the design phase of components. They derived four comprehensive process maps using data and models from published literature, which enable the prediction of a component's energy consumption during machining based on the geometric features of the component. Three case studies were conducted and showed that, the specific energy consumption for machining decreases with higher material removal rates. They revealed that the relationship is not linear, but can be regressed as a power function. Pantazis et al. (2023) developed a virtual machining energy toolkit to predict the electrical power required to machine a component using instructions from NCs and workpiece geometry. Good correlation between the predicted and measured energy consumption having a mean average percentage error of 4.3%.

Table 2. 1: Summary of energy consumption models for toolpaths based on NC codes

AUTHOR	MODEL	CONTRIBUTION AND LIMITATION
Avram & Xirouchakis, 2011	$E_{total} = E_{as} + E_{run} + E_{aY} + E_{dY} + E_{sY} + E_{cut}$ Where E_{total} is the total energy demand the machine tool, E_{as} is energy for acceleration speed of the spindle, E_{run} is the energy required to overcome mechanical losses, E_{aY} is energy for acceleration of the feed axis, E_{dY} is energy for deceleration of the feed drive, E_{sY} is the energy required to move the feed axis at constant speed, E_{cut} is the energy required for cutting process.	A model for energy consumption by machine tool based on toolpaths was developed; the model was validated; weight of the work piece was not considered in their model; circular interpolation codes were not considered; energy demand software was not developed for the model.
Diaz et al., 2011	$E = (P_{cut} + P_{air})\Delta t$ Where E is the total energy demand, P_{cut} is power required for material removal, P_{air} is air cutting power and Δt is the processing time.	A model for energy consumption by machine tool based on toolpaths was developed; weight of the work piece was not considered in their model; NCs were not used to for validating the model; software was not developed for the model.
Mori et al., 2011	$E_{total} = P_1(T_1 + T_2) + P_2 T_2 + +P_3 T_3$ Where, E_{total} is the total direct energy requirements; P_1, P_2, P_3 represent basic, idle and cutting power demand. T_1, T_2, T_3 are their corresponding time duration.	Developed a model for electrical energy demand based on NCs; the model was not validated; weight of the work piece was not considered in their model; energy demand software was not developed.
Kong et al., 2011	$E_{total} = E_{constant} + E_{run\ time\ transient} + E_{run\ time\ steady} + E_{cut}$ Where E_{total} is the total energy demand of the machine tool, $E_{constant}$ is the energy consumed in the idle state of the machine, $E_{run\ time\ transient}$ is the energy required by the feed axis drives and spindle to accelerate or decelerate to reach the required speed, $E_{run\ time\ steady}$ is the energy consumed by the feed drive system	CNC energy consumption model was developed; web based application programming interface, based on process analysis software tools were developed to estimate energy consumption in CNC machining; weight of the work piece was not considered; circular interpolation was not considered.

	at constant speed and E_{cut} is the energy required for the material removal process.	
Aramcharoen & Mativenga, 2014	$E_{total} = E_{basic} + E_{tool} + E_{spindle} + E_{cutting} + E_{feed} + E_{coolant}$ where E_{total} is the total energy demand of the machine tool, E_{basic} is the energy required to keep the machine in the idle state, E_{tool} is the energy consumption required for tool change, $E_{spindle}$ is the energy required by the spindle, $E_{cutting}$ is the energy for material removal, E_{feed} is the energy consumption of the feed drives system, $E_{coolant}$ is the energy required by the coolant pump motor.	Developed a model for electrical energy demand based on NCs; weight of the work piece was not considered; circular interpolation codes were not validated; energy demand software was not developed.
Guo et al., 2015	$E_{total} = E_{RMT} + E_{MRM} + E_{PTM}$ where E_{total} is the total energy demand for machining a product, E_{RMT} is the energy required for rapid movement of the feed axes, E_{MRM} is the energy required for material removal, E_{PTM} is the energy required for process transition mode.	Developed model based on NCs and simulated energy demand for the machining processes. Weight of the work piece was not considered;
Pavanaskar & McMains, 2015	$E_{block} = t * P_{tare} + t * P_{coolant\ pump} + t * P_{feed} + t * P_{spindle} + t * P_{cut}$ Where E_{block} is the energy consumed by a block of NC code; P_{tare} is the constant power consumption of the machine in the idle state; $P_{coolant\ pump}$ is the power consumption of the coolant pump; P_{feed} is the power required for movement of the feed axes, $P_{spindle}$ is the power require for rotation of the spindle, P_{cut} is the power	Developed web-based software for computing energy demand based on NCs; weight of the work piece was not considered; circular interpolation codes were not validated.

	required for material removal; t is the time duration for a given block of NC.	
Altıntaş et al., 2016	$E_{feature} = E_{basic} + E_{auxiliary} + E_{metal\ cutting}$ Where $E_{feature}$ is the total energy required to machine a particular feature, E_{basic} is the energy consumed when the machine tool is in its idle state; $E_{auxiliary}$ is the energy consumed by systems which enhance the quality of the cutting system, such as the coolant system; and $E_{metal\ cutting}$ is the energy required for material removal.	Developed energy model which computes energy consumption based on NCs; optimized energy consumption based on different cutting parameters; energy demand software was not developed; weight of the work piece was not considered; circular interpolation was not considered.
Balogun et al., 2016	$E_{total} = P_b(t_b + t_r + t_c) + P_r t_r + P_{tc} t_{tc} \left[INT\left(\frac{t_c}{T}\right) + 1 \right] + P_{air} t_{air} + (mN + C + P_{cool} + kv)t_c$ Where E_{total} is the total energy demand for the CNC machine, P_b and P_r are the basic and ready-state power of the machine, respectively. P_{tc}, P_{air} and P_{cool}, are power demand for tool change, air cutting, and coolant system respectively. t_b, t_r, t_{tc}, t_{air}, t_c and T represent setup time, ready state time, tool change time, air cutting time, cutting time and tool life respectively, and $mN + C$ expresses the power consumed by the spindle, where N is the rotational speed of the spindle, m and C are constants to be determined experimentally.	Developed energy model based on NCs and a software for estimating energy consumed by the CNC machine; the model considers tool change; weight of the work piece was not considered; circular interpolation codes were not validated;
Edem & Mativenga, 2017b	$E_{total} = E_{baseline} + E_{tool\ change} + E_{spindle\ run} + E_{cut} + E_{feed} + E_{coolant}$	Developed energy model based on NCs; developed a software for estimating energy demand of the CNC machine; the model developed considered weight of the work piece; the model supports tool

	Where; E_{total} is the total electrical energy required for CNC machining, $E_{baseline}$ is the energy required by auxiliary and peripheral units, $E_{tool\ change}$ is the energy consumption of the tool change process, $E_{spindle\ run}$ is the energy required for spindle rotation, E_{cut} is the energy required for material removal, E_{feed} is the energy consumption of the feed drives, and $E_{coolant}$ is the energy consumption of the coolant pump motor.	change; energy consumption for circular interpolation was not validated; the model requires weight of the feed axis to be known.
L. Zhou et al., 2017	$E_{in\ cut} = E_{standby} + E_{spindle} + E_{feed} + E_{material}$ Where; $E_{in\ cut}$ is the total energy demand for the CNC machine, $E_{standby}$ is the energy consumption in the stand-by mode, $E_{spindle}$ is the energy demand of the spindle, E_{feed} is the energy demand of the feed drive system, $E_{material}$ is the energy required for material removal.	Developed energy model based on NCs for CNC machine; the model developed does not considered weight of the work piece; circular interpolation codes were not validated; the model does not support tool change; energy demand software was not developed.
Pawanr et al., 2021	$E_{total} = E_{steady} + E_{transient}$ $E_{steady} = E_{standby} + E_{idle} + E_{ready} + E_{cutting}$ $E_{transient} = E_{startup} + E_{spindle_acl} + E_{feed_tr} + E_{coolant_tr}$ Where E_{total} is the total energy consumption of the machine tool. E_{steady} and $E_{transient}$ are the energy consumption during the steady state and transient state respectively. $E_{standby}$ is the energy consumed in standby state. In this state, the cooling fans, hydraulic systems, control unit and display devices are in an active condition to ensure the normal functioning of a machine tool. E_{idle} is energy	Developed energy model based on NCs for predicting energy consumed by the CNC machine; the model accounts for both steady energy states and transient energy states; the model developed does not considered weight of the work piece; energy demand software was not developed for the model.

	consumption in the idle state. In this state, the spindle is running at target speed and the machine is in operational readiness. E_{ready} is the ready state energy consumption, in which feed drive is also activated without cutting. $E_{cutting}$ is the energy consumption due to material removal. $E_{startup}$ is the start-up state energy consumption. This is the transient state before the standby steady state. $E_{spindle_acl}$ the spindle acceleration energy consumption. E_{feed_tr} is the feed start energy consumption during which there is a sudden power peak arises. $E_{coolant_tr}$ is the coolant pump start-up energy consumption.	
Feng et al., 2021	$E_{NC-block} = E_{standby} + E_{coolant} + E_{tool\ change} + E_{rapid} + E_{spindle} + E_{feed} + E_{cut}$ Where $E_{NC-block}$ is the energy to be consumed by an NC block. $E_{standby}$ constitutes energy demand of the controller, lights, etc. $E_{coolant}$ is the energy required by the coolant pump motor. $E_{tool\ change}$ is the energy required for tool change. E_{rapid} is the energy demand for rapid movement of the feed axes. E_{feed} is the energy demand for movement of the feed drive system. $E_{spindle}$ is the energy demand for spindle rotation. E_{cut} is the energy demand for material removal.	Developed energy model based on NCs for CNC machine; the model supports tool change; circular interpolation codes were not validated; the model developed does not considered weight of the work piece; energy demand software was not developed.
L. Zhou et al., 2021	$P_{in\ cut} = P_{standby} + P_{spindle} + P_{feed} + b_1 + n^{b_2} + MRR_m$ Where $P_{in\ cut}$ is the total power demand for the CNC machine, $P_{standby}$ is the power consumption in the stand-by mode, $P_{spindle}$	Developed energy model based on NCs for CNC machines; the model developed does not considered weight of the work piece; circular interpolation codes were not validated; The model does not support

	is the power demand of the spindle, P_{feed} is the power demand of the feed drives, n is the rotational speed of the spindle, MRR_m is the material removal rate. b_1 and b_2 are constants to be determined experimentally. The individual power states are multiplied by corresponding time intervals to obtain energy demand of the CNC machine.	tool change. Energy demand software was not developed.
(Pantazis et al., 2023)	$E_k = P_k * t_k$ Where E_k is the energy demand for a given machining process, P_k represents the average power consumption for a sub operation and t_k is the time duration of the sub-operation. Sub-operations considered are; spindle acceleration, air-cutting, rapid axis movement and material cutting.	Developed energy model based on NCs and a software for estimating energy consumption of the CNC machine; circular interpolation codes were not validated; the model developed does not considered weight of the work piece
Feng et al., 2023	$E_{sum} = E_{constant} + E_{variable}$ $E_{constant} = E_{lub} + E_{hyap} + E_{aux} + E_{control} + E_{other}$ $E_{variable_i} = E_{tool\ change_i} + E_{spindle_i} + E_{feed_i} + E_{coolant_i} + E_{material_i}$ Where E_{sum} is the total energy demand of the machine tool. The fixed energy demand is denoted by $E_{constant}$, and the variable energy demand is denoted by $E_{variable}$. E_{lub} is lubrication sub-system and cooling sub-system energy demand, E_{hyap} is hydraulic and pneumatic sub-system energy demand, E_{aux} is auxiliary sub-system energy demand, $E_{control}$ is the control sub-system energy demand, E_{other}	Developed energy model based on NCs; developed a software for estimating energy consumption in CNC machining; the model supports tool change; The model developed does not considered weight of the work piece

	is energy demand from other sub-systems, $E_{tool\ change_i}$ is the energy consumption when changing the cutting tool, $E_{spindle_i}$ represents the energy consumption of the spindle, E_{feed_i} is the energy consumption of feed drive system, $E_{coolant_i}$ is the energy consumption of coolant system and $E_{material_i}$ is the energy consumption of material removal.	
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2.3 Energy efficient tool pathways

Pavanaskar & McMains (2015) measured the energy required for facing a rectangular block using a CNC machine. They showed that different tool pathways for machining the same rectangular block did not consume the same amount of energy. Figure 2. 1 shows the different pathways which they generated for facing a rectangular block.

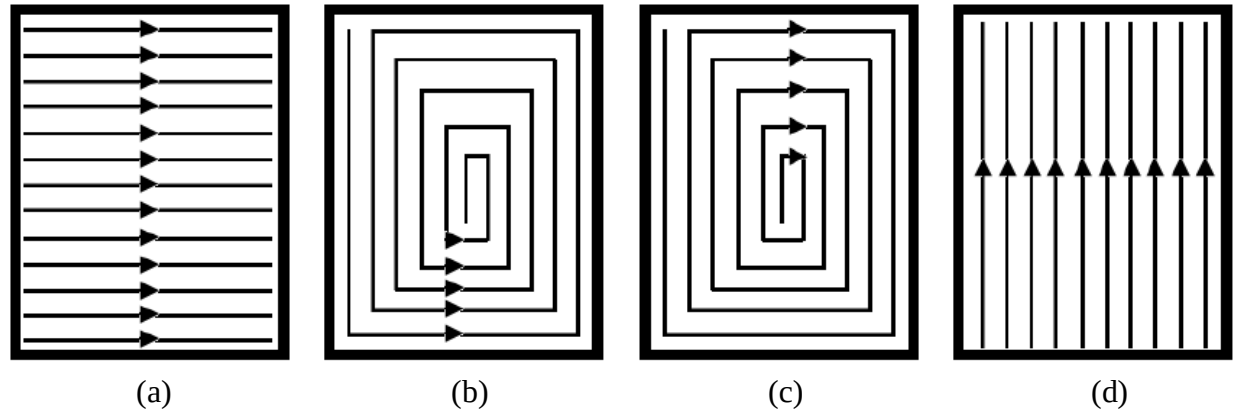


Figure 2. 1: Schematics of four tool pathways (S. Pavanaskar & McMains, 2015)

Table 2. 2 shows the total amount of energy which was consumed when using the four different pathways to machine the rectangular block. The machining process was carried out on a Haas VF-0 CNC machine. The table also shows the total energy which they estimated for the different tool pathways using the energy model which they developed. They were able to predict the energy consumed within a minimum percentage deviation of -6% and a maximum of 3%.

Table 2. 2: Validation of NC codes (toolpaths)

Cutting pathway	Energy estimated (J)	Energy measure (J)	Time Estimates (s)	Time Measured (s)	% Deviation (time)	% Deviation (energy)
Facing, X directional (a)	109,876	106,475	286	290	-1	3
Spiraling in (b)	109,223	114,542	262	265	-1	-4
Spiraling out(c)	123,871	130,652	267	280	-4	-6
Facing, Y directional (d)	147,190	142,601	291	287	1	3

The results shown in Table 2. 2 reveal that the total energy required for machining in the x-axis direction is less than the total energy required for machining in the y-axis direction. Therefore it will be more advantageous to select tool pathway which has greater motion in the x-axis direction than the y-axis direction. The results in Table 2. 2 also shows that spiraling inwards and spiraling

outwards do not consume the same amount of energy, and for Haas VF-0 3-axis CNC machine, spiraling inwards, consumes less energy.

Pavanaskar & McMains (2015) went on to conduct a case study to analyze the zigzag tool pathway strategy, with one being oriented in the x-axis direction and the other in the y-axis direction. The two tool pathways are shown in Figure 2. 2. The energy and time duration results obtained for the two tool pathways strategies is shown in Table 2. 3.

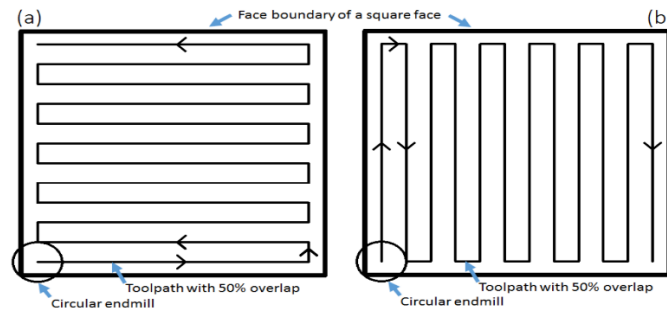


Figure 2. 2: (a) Zigzag tool pathway in the x-axis direction (left). (b) Zigzag tool pathway in the y-axis direction (right)

Table 2. 3: Energy consumption and time estimates toolpath strategies

Toolpath strategy	Energy (J)	Time(s)
X-directional facing (a)	106 241	324
Y-directional facing (b)	130 497	318

The machining time duration for the two toolpaths is nearly equal, however facing with toolpath orientation along the x-axis direction consumes considerably less energy, 20% less, than when facing along the y-axis direction. Pavanaskar & McMains (2015) explained that the energy consumption differences are due to differences in feed axes construction, motor capacities, and the bearing sizes. They further stated that, the Haas VF-0 machine has the x-axis mounted on top of the y-axis, as a result, when machining in the y-axis direction, the whole mass of the x-axis motors, bearings, and guides move as well. They stated that this may be the other reason for the difference in energy consumption of the two axes.

Pavanaskar & McMains (2015) went on to perform two case studies, with the contour tool pathway strategy and the spiral-in tool path strategy. The contour tool pathway strategy consumed more energy in some work-piece geometries while and in some geometries, it consumed lesser energy, as compared to spiral-in tool path strategy. Results from their studies showed that the energy efficiency of tool pathway strategies is also dependent on the geometry of the cut. Vila et al. (2015) further investigated how aligning the zigzag toolpath strategies along the x-axis and along the y-axis, affected energy consumption. The concluded that less energy was consumed when the toolpath strategy was aligned along the x-axis.

Edem et al. (2017) studied the impact of tool pathway strategies on the electrical energy demand in milling machining. This study was conducted on two different three axis CNC milling

machines; the Takisawa Mac-V3 milling machine and the Mikron HSM400 milling machine. From experiments conducted they deduced that energy efficiency of tool pathway strategies is dependent on the CNC machine. They stated that this was due to factors such as the feed axis configuration, the type of feed motors used, as well as the feed drive type.

Kiswanto et al. (2018) compared the total energy consumed by three different tool pathway strategies in four case studies. The geometries to be machined are as shown below in Figure 2. 3. The results showing the total energy consumption for the three different tool pathway strategies in all the four case studies is shown in Table 2. 4.

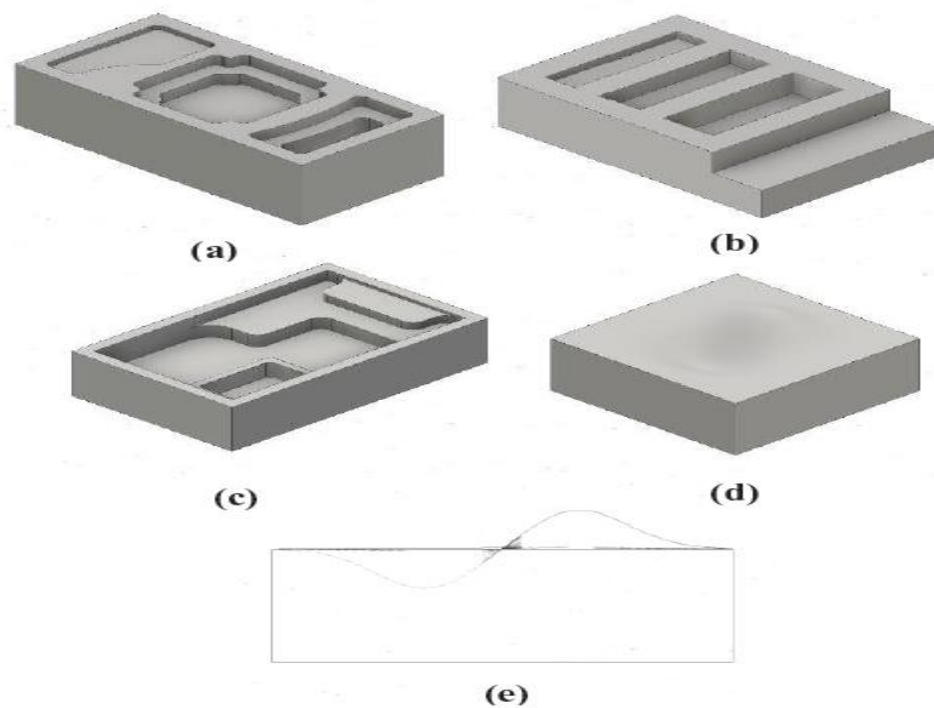


Figure 2. 3: Parts used for this study: (a) Part Prismatic I, (b) Part Prismatic II, (c) Part Prismatic III, (d) Part Sculptured, and (e) Part Sculptured front view (Kiswanto et al., 2018).

Table 2. 4: Total Energy Consumption in CNC machining (Kiswanto et al., 2018).

Workpiece	Tool pathway Strategy	Total Energy Consumption (kJ)
Prismatic Part I	Follow Part	6289.49
	Follow Periphery	6321.65
	Zig Zag	5342.21
Prismatic Part II	Follow Part	21681.25
	Follow Periphery	19554.47
	Zig Zag	17204.92
Prismatic Part III	Follow Part	18667.26
	Follow Periphery	17292.93
	Zig Zag	15170.32
Sculpture Part	Follow Part	48976.55
	Follow Periphery	49587.96
	Zig Zag	49273.59

From the results shown in Table 2. 4, Kiswanto et al. (2018) concluded that, the tool pathway strategy which is more energy efficient in all the four case studies is the zigzag tool pathway strategy. They stated that the total energy savings when machining by zigzag tool pathway, compared to the other two tool pathway strategy for the three prismatic components are; 15.48%, 20.64% and 18.73% respectively.

Edem et al. (2019) conducted a study to determine energy efficient toolpaths using NC-based energy demand software. To achieve this, they generated NC programs for true spiral, rectangular spiral, and square contour toolpaths using Hypermill CAM software. These NC programs were used to machine rectangular pockets on AISI 1018 steel blocks using a 3-axis CNC milling machine. The total electrical energy requirements for running NC programs generated for pocket milling with true spiral, rectangular spiral, and square contour toolpaths were predicted to be 303, 342, and 358 kJ respectively using the NC-based energy demand prediction software, while the measured total electrical energy requirements were 311, 358, and 374 kJ respectively. It was also observed that the true spiral toolpath resulted in energy savings of 15% and 20% when compared with the rectangular spiral and square contour toolpaths respectively. The measured total electrical energy demand correlates with the results from the NC code-based software by 2.6%, 4.7%, and 4.5% respectively.

Lazo et al. (2022) studied impact of the toolpath selection on energy consumption, machining time, and surface quality when milling 6061-aluminium alloy. They stated that a combination of the cutting parameters and the toolpath strategy could be selected to reduce machining time, energy consumed and surface roughness. Experimental results showed that there was up to 69% reduction in machining time and 13% reduction in energy consumption if the spiral trajectory was used.

2.4 Research gap

CNC energy consumption models developed did not consider weight of the work piece, except model by Edem & Mativenga (2017). Although the model by Edem & Mativenga (2017)

considered weight of the work piece, it requires one to know the weight of the feed axis system. The model proposed in this study considers weight of the work piece, however, it does not require weight of the feed axis system to be known. Previous models also did not show how circular interpolation energy consumption is computed using the energy models, hence circular interpolation NCs were not validated. CNC energy consumption software developed assumed that the machining percentage overlap was constant throughout the machining process. This assumption reduces the accuracy of the software, as percentage overlap usually varies during machining. This study eliminates this assumption from software computations. This study also improves the user-friendliness of previously developed software.

2.5 Conclusion

Considerable amount of work has been carried out by various researchers to develop models for energy consumption in CNC machining. These energy models were then used successfully to optimize energy consumption in CNC machining. This work presented in this thesis will address research gaps presented in section 2.4.

Chapter 3: METHODOLOGY

3.1 Introduction

In this chapter, procedures carried out to achieve objectives of the thesis are described. The experimental set-up used for studying energy consumption in CNC machining is presented. Data obtained from this experimental set-up is used in developing the CNC energy consumption model and determining constants for the model. The energy model is used in developing the CNC energy analyzer software. Data from the experimental set-up will be used to validate the energy model and the energy analyzer software. Lastly data from the experimental set-up is used to analyze tool pathway strategies with respect to energy consumption.

3.2 Experimental set-up

The CNC machine used in this study is the Emco concept mill 55 CNC machine, shown in Figure 3. 1. The Emco concept mill 55 CNC machine is a three axis CNC milling machine. This CNC machine was used to conduct controlled experiments to obtain data used in this thesis. These experiments were carried out in BIUST, students' workshop.



(a)



(b)

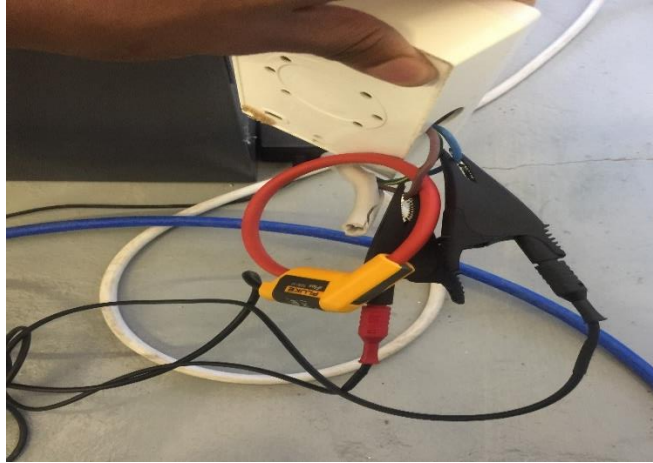
Figure 3. 1; (a) Emco concept mill 55 CNC machine; (b) Emco concept mill 55 CNC machine with the door open.

The energy consumption of the CNC machine was measured using the Fluke 1738 power logger shown in Figure 3. 2. The Fluke power logger displays measurements of electric current, voltage, power and energy consumption of a given device. The power logger is capable of recording these data parameters at intervals of 1 second.

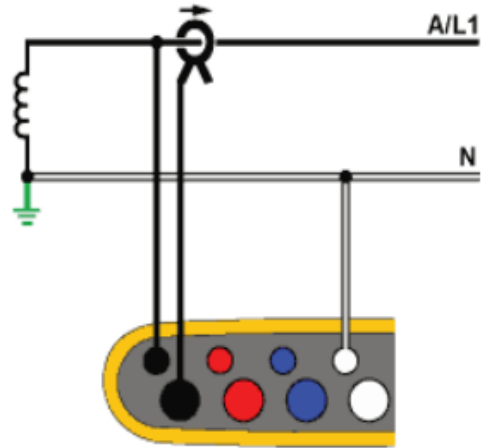


Figure 3. 2 Fluke 1738 power logger

In order to measure the power demand of various components of the CNC machine and the total energy consumed by the CNC machine, electric connection shown in Figure 3. 3 were made. A/L1 represents the live wire and N represents the neutral wire. With these connections, electric current, voltage, power and energy consumed by the CNC machine were measured at intervals of 1 second.



(a)



(b)

Figure 3. 3: (a) Electric connections made to CNC machine; (b) Schematic of the connections made (Fluke Corporation, 2015)

With this experimental set-up, individual components of the CNC machine could be targeted by actuating them in controlled experiments to observe how different components of the CNC machine consume electric energy. With this approach the total energy consumed by a CNC machine, was categorized into different energy divisions. Each energy division has its own corresponding power state. The analysis of the energy divisions and their power states is dealt with, in chapter 4.

3.3 Data analysis

Data from Fluke power logger was analyzed using fluke energy analyzer plus software. This software presents data in graphs like the one shown in Figure 3. 4. This graph shows the power consumption for cutting along the x-axis direction at feedrate intervals of 10 mm/min, starting at 10 mm/min. The cutting was performed on an aluminum 6160 block, shown in Figure 3. 4.

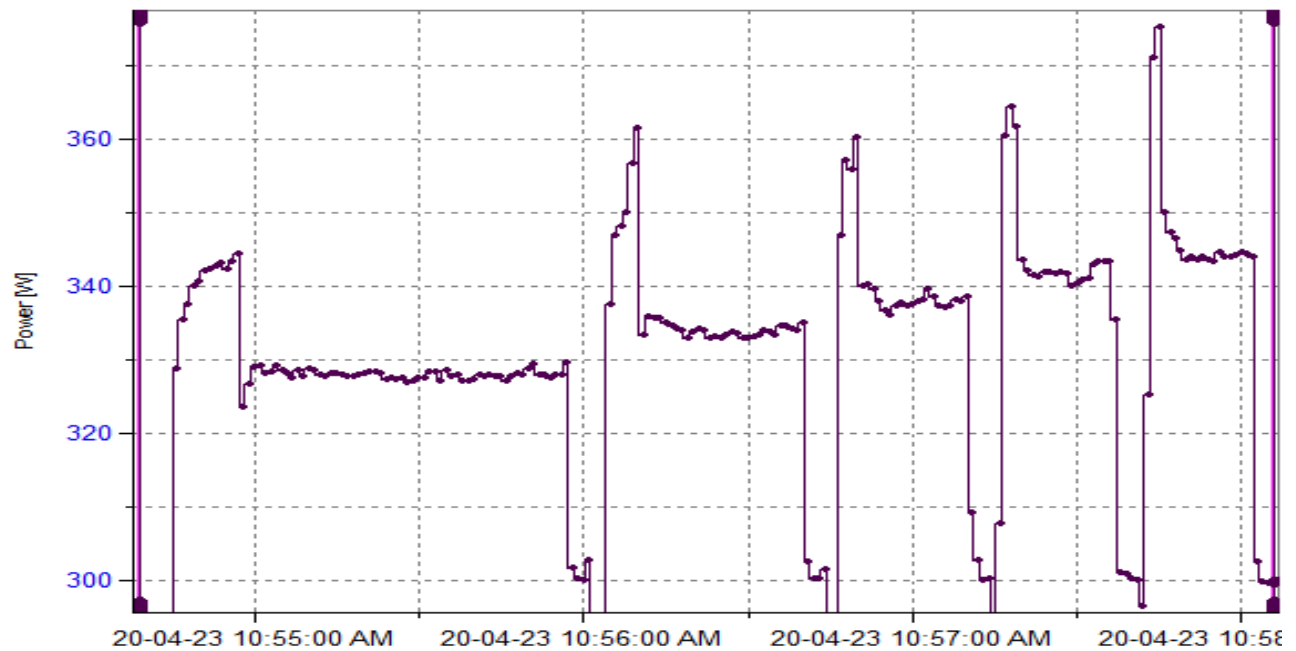


Figure 3. 4: Power consumption for cutting along the x-axis direction, at feedrate intervals of 10 mm/min, starting at 10 mm/min



Figure 3. 5: Cuts produce at different feedrates, along the x-axis and y-axis directions

Machining trial shown in Figure 3. 5 and data shown in Figure 3. 4 were used to study the effects of material removal rate on energy consumption in CNC machining. The other energy divisions were also analyzed using fluke energy analyzer plus software. These analyses are presented in chapter 4.

Data for analyzing tool pathway strategies and for validating the CNC energy consumption model and the CNC energy analyzer software were also analyzed using fluke energy analyzer software. Figure 3. 6 shows the data collected for milling a rectangular pocket using the pocket-in tool pathway strategy. This rectangular pocket was produced on an aluminum 6160 block shown in Figure 3. 7.

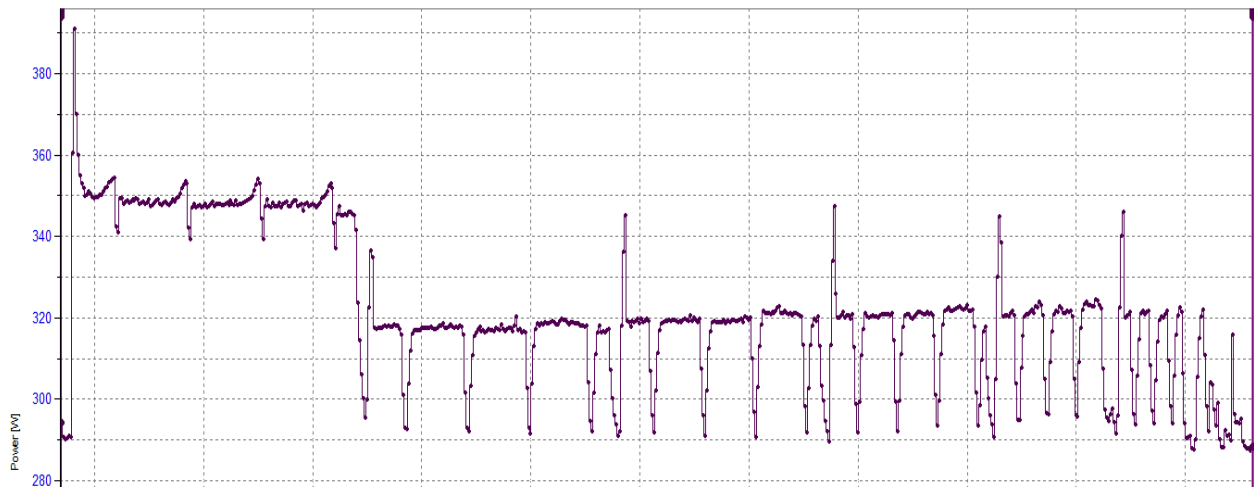


Figure 3. 6: Power consumption for milling rectangular pocket on an aluminum block using pocket-in tool pathway strategy.

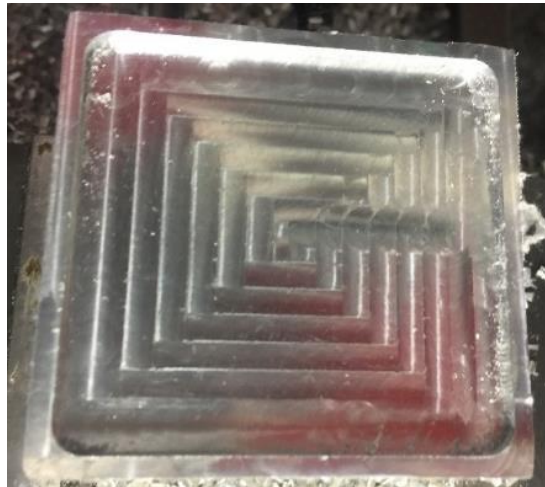


Figure 3. 7: Square pocket produced using pocket-in tool pathway strategy.

Eight other tool pathway strategies were analyzed the same way. A detailed presentation of these analyses is presented in chapter 6.

3.4 Conclusion

This chapter has presented the experimental set-up for this thesis and how the data will be analyzed. The next chapters will use data obtained in this experimental set-up to:

- Develop the CNC energy consumption model (Chapter 4)
- Develop the CNC energy analyzer software (Chapter 5)
- Validate the CNC energy consumption model (Chapter 6)
- Validate the CNC energy analyzer software (Chapter 6)
- Analyze tool pathway strategies with respect to energy consumption (Chapter 6)

Chapter 4: PROPOSED ENERGY MODEL

4.1 Introduction

This thesis proposes a novel CNC energy consumption model with the aim of improving the accuracy and applicability of energy models developed previously by other researchers. The proposed model predicts energy to be consumed during machining, having its input as the NC. This model has constants which are determined empirically using the experimental set-up shown in chapter 3. The model will then be used in developing a software, which is discussed in chapter 5.

The total energy consumed by a CNC machine is given by summation of the energy consumed by each block of the NC as shown in equation ((4.1) (Pavanaskar & McMains, 2015). This approach will be used in developing the CNC energy consumption model in this thesis. With this approach, the geometric aspects of the toolpaths are incorporated into the CNC energy consumption model.

$$E_{total} = \sum E_{block} \quad (4.1)$$

Where: E_{total} is the total energy consumed by the CNC machine; E_{block} is the total energy consumed by each block of NC.

The energy model presented in this thesis categorizes the energy consumed by a CNC machine into different energy divisions. This allows energy consumption of different components of the CNC machine to be analyzed in isolation. The energy model used for computing total energy consumption in CNC machining is given by the equation (4.2) below.

$$E_{block} = E_{fixed} + E_{coolant_pump} + E_{spindle} + E_{rapid} + E_{linear_int} + E_{circular_int} + E_{tool_change} \quad (4.2)$$

Where: E_{block} is the total energy consumed by each block of NC; E_{fixed} is the energy consumption for just keeping the machine on, without running the NC. $E_{coolant_pump}$ is the energy consumption of the coolant pump; $E_{spindle}$ is the energy consumption for spindle rotation; E_{rapid} is the energy consumption for movement of the feed axis during rapid motion; E_{linear_int} is the energy consumption for linear interpolation cutting; $E_{circular_int}$ is the energy consumption for circular interpolation cutting; E_{tool_change} is the energy consumption for tool change process.

4.2 Analysis of individual energy division

Energy consumption for each block of NC can be associated with one or more energy divisions. With each energy division having its own power state and corresponding time duration, the energy consumption of each block of NC due to different energy divisions in CNC machining is evaluated using equation (4.3). Where E_{block} is the energy consumption of a given block of NC, P_{state} is the mean power consumption corresponding to a given energy division and t_{state} is its corresponding time duration. Each energy division has its own corresponding power state. These power states are discussed from section 4.2.1 to section 4.2.7.

$$E_{block} = \sum P_{state} * t_{state} \quad (4.3)$$

All power states discussed in this section are measured using the experimental set-up which was presented in chapter 3. Although the model developed in this thesis is applicable to any three axis CNC milling machine, the energy model constants determined in this thesis are specific to the Emco concept mill 55 CNC machine. However, the method for determining the energy model constants, discussed in this thesis, can be used to determine these constants for any three axis CNC milling machine.

4.2.1 Fixed energy consumption

Fixed energy consumption E_{fixed} , is given by equation (4.4), where P_{fixed} is the mean power consumption for just keeping the machine on, without running the NC while t_{fixed} is its corresponding time duration.

$$E_{fixed} = P_{fixed} * t_{fixed} \quad (4.4)$$

The fixed power state, P_{fixed} , is constant. It does not change with respect to any machining parameter. This is the power measured just before the CNC machine begins to execute the NC. For the Emco concept mill 55 CNC machine, the fixed power measured was 161 watts.

The time duration for the fixed power state t_{fixed} for each block of NC is given by equation (4.24) or equation (4.38), depending on the on the G-code. For G00 and G01 codes, equation (4.24) is utilized to compute time duration for the fixed power state. For G02 and G03 codes, equation (4.38) is utilized to compute time duration for the fixed power state.

4.2.2 Coolant pump energy consumption

Coolant pump energy consumption $E_{coolant_pump}$, is given by equation (4.5), where $P_{coolant_pump}$ is the mean power consumption of the coolant pump while $t_{coolant_pump}$ is its corresponding time duration.

$$E_{coolant_pump} = P_{coolant_pump} * t_{coolant_pump} \quad (4.5)$$

The coolant pump power state, $P_{coolant_pump}$, is also constant. This is the power consumption for activation of the coolant system. M08, is the M-code which activates this power state. The Emco concept mill 55 CNC machine, does not have this coolant system, the coolant pump power is recoded to be 0 watts.

The time duration for actuation of the coolant pump $t_{coolant_pump}$ for each block of NC code is given by equation (4.24) or (4.38), depending on the on the G-code. For G00 and G01 codes, equation (4.24) is utilized to compute time duration for actuation of the coolant pump. For G02 and G03 codes, equation (4.38) is utilized to compute time duration for actuation of the coolant pump.

4.2.3 Spindle rotation energy consumption

Spindle rotation energy consumption $E_{spindle}$, is given by equation (4.6), where $P_{spindle}$ is the mean power consumption for spindle rotation while $t_{spindle}$ is its corresponding time duration.

$$E_{spindle} = P_{spindle} * t_{spindle} \quad (4.6)$$

The spindle power state, $P_{spindle}$, is modeled using a linear regression model given by equation (4.7). This power state is activated by M03 code, for clockwise rotation, or the M04 code, for counter-clockwise rotation of the spindle.

$$P_{spindle} = mN + k \quad (4.7)$$

Where; m and k are constants to be determined experimentally. N is the rotational speed of the spindle.

The time duration for the spindle rotation power state, $t_{spindle}$, for each block of NC is given by equation (4.24) or equation (4.38), depending on the on the G-code. For G00 and G01 codes, equation (4.24) is utilized to compute time duration for the spindle rotation power state. For G02 and G03 codes, equation (4.38) is utilized to compute time duration for the spindle rotation power state.

For the Emco concept mill 55 CNC machine, a system of piece-wise linear equations for predicting energy consumption for spindle rotation is deduced. This is because the power consumption with respect to spindle rotational speed forms different linear regression models for different spindle speed intervals as shown in Figure 4. 1 . This phenomenon has been shown to be common to other models of CNC machines (Balogun & Mativenga, 2013; Feng et al., 2021).

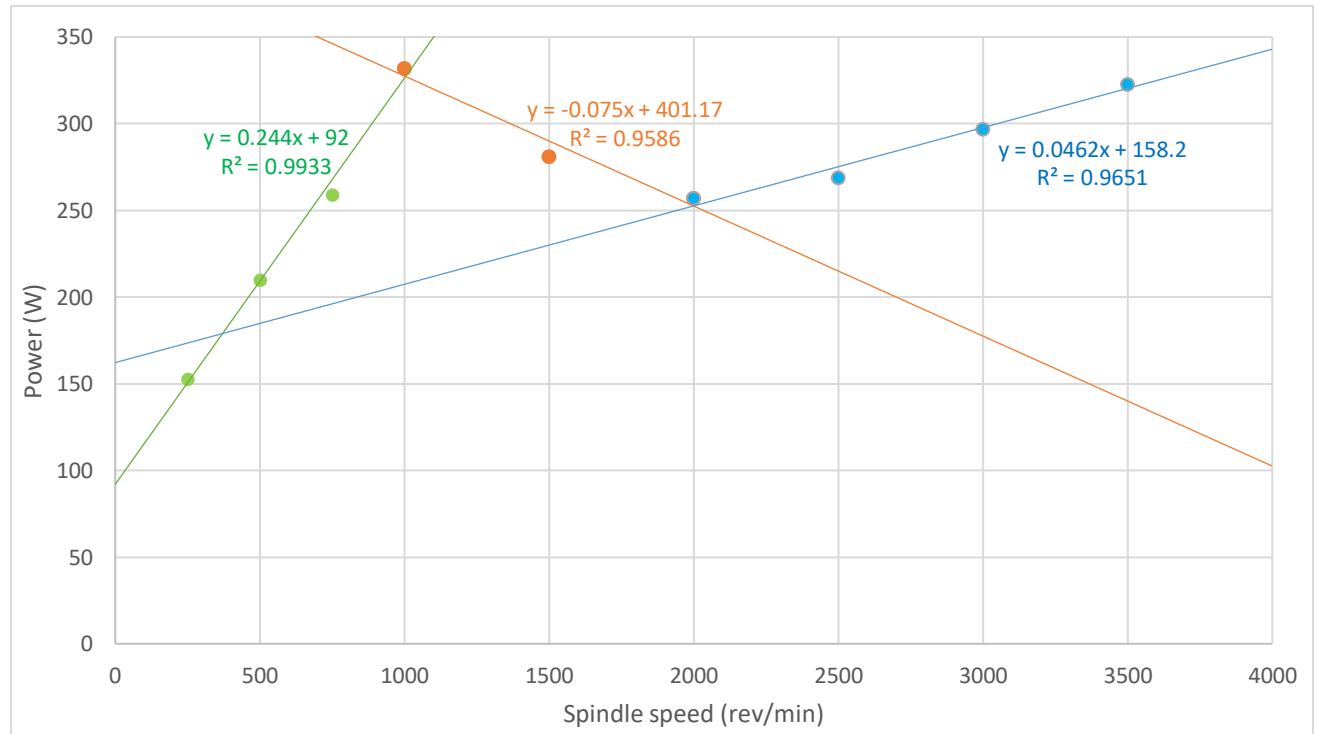


Figure 4. 1: A graph for spindle rotation power consumption against spindle speed

Linear regression equations shown in Figure 4. 1 are used to determine constants for equation (4.7). First the fixed power, 161 watts, is deducted from linear regression equations shown in Figure 4. 1. The resulting equations are then substituted into equation (4.7) to determine constants for spindle rotation power in the Emco concept mill 55 CNC machine. The resulting equation, equation (4.8), gives the power consumption of the spindle with respect to rotational speed, N .

$$P_{spindle} = \begin{cases} 0.244N + 69.0 & 0 < N \leq 1000 \\ -0.075N + 240.2 & 1000 < N \leq 2000 \\ 0.0462N - 2.8 & 2000 < N \leq 3500 \end{cases} \quad (4.8)$$

4.2.4 Rapid movement energy consumption

Rapid movement energy consumption E_{rapid} , is given by equation (4.9). Where, P_{feed} is the mean power consumption of the feed drive system, with t_{feed} being its corresponding time duration.

$$E_{rapid} = P_{feed} * t_{feed} \quad (4.9)$$

The mean power consumption of the feed drive system, P_{feed} , varies with respect to the feedrate. From the literature review of energy models, discussed in chapter 2, it has been observed that this power consumption was successfully modeled into a linear regression model with respect to feedrate. Pavanaskar & McMains (2015) expressed the power consumption of the feed drive system using equation (4.10). Where KA_{move_i} and KB_{move_i} are constants to be determined experimentally. F_i is the feedrate.

$$P_{feed} = \sum_{i=x,y,z} \left(KA_{move_i} + (KB_{move_i} \times F_i) \right) \quad (4.10)$$

Considering motion in only one axis, first, in the x-axis direction. Equation (4.11) will be written in this form:

$$P_{feed_x} = KA_{move_x} + (KB_{move_x} \times F_x) \quad (4.11)$$

This approach used by Pavanaskar & McMains (2015) neglects the effect of workpiece weight on the energy consumption of the CNC machine. Most of the energy models discussed in chapter 2 have used this approach in modelling energy consumption of the feed drive system (Sarikaya et al., 2022). Edem & Mativenga (2016) introduced an approach which considers the effect of workpiece weight in energy consumption of CNC machines. In considering power consumption

of the feed drive system, Edem & Mativenga (2016), developed a model which is dependent on two variables, feedrate and weight of; the feed drive system, machine vice and workpiece. The model which they developed for power consumption of the feed axis drive system is shown in equation (4.12). In this equation, a and b are constants to be determined experimentally, v_{fx} is the feedrate in the x-axis direction. W is weight of; the feed drive system, machine vice and workpiece.

$$P_{feed_x} = (aWv_{fx} + bW) \quad (4.12)$$

Equation (4.12) is used in deriving power consumption of the feed drive system in CNC machining for this thesis. The aim is to develop a model which has weight of the work piece as a variable but excludes weight of the feed drive system and the vice. This is because determining weight of the feed drive system and the vice may be a long and labour-intensive process. By separating the weight of the work piece from the weight of the feed drive system and the vice, equation (4.13) is deduced. Where W_a is the weight of; the feed drive system and the vice, while W_w is the weight of the work piece. Expanding equation (4.13) gives equation (4.14). It should be noted that the weight of the feed drive system and the vice, W_a , is constant in a given CNC machine, and is treated as such in equation (4.15). In equation (4.15), A and B are additional constants to be determined experimentally.

$$P_{feed_x} = a(W_a + W_w)v_{fx} + b(W_a + W_w) \quad (4.13)$$

$$P_{feed_x} = aW_av_{fx} + aW_wv_{fx} + bW_a + bW_w \quad (4.14)$$

$$P_{feed_x} = Av_{fx} + aW_wv_{fx} + B + bW_w \quad (4.15)$$

Equation (4.15) computes power consumption for movement of the feed system. It considers the weight of the work piece. Unlike the approach used by Edem & Mativenga (2016), this equation does not require weight of the feed drive system and the vice to be known. Equation (4.15) is expressed in the form shown in equation (4.16), to account for the energy consumption for all the three axes (x,y,z). The symbols for constants have been altered to keep consistency in the model presented in this thesis.

$$P_{feed} = \sum_{i=x,y,z,-z} a_i W f_i + b_i W + c_i f_i + q_i \quad (4.16)$$

In equation (4.16), a_i , b_i , c_i and q_i are constants to be determined experimentally. f_i is the feedrate while W is the weight of the work piece only. Comparing this model with the model by Pavanaskar & McMains (2015) shown by equation 4.12, it can be seen that the model by Pavanaskar & McMains (2015) considers only the last two terms in equation (4.16), but neglects the first two terms, which are responsible for power consumption due to weight of the work piece.

The feed drive system power state is activated by the rapid move code, G00. Point 1 in Figure 4. 2 represents the starting point of the cutting tool while point 2 represents its end point in rapid movement. Let x_1 , y_1 , z_1 represent the coordinates of the starting point while x_2 , y_2 , z_2 represents coordinates of the end point in millimeters. The syntax for the G00 code is then given by:

$$G00 \ Xx_2 \ Yy_2 \ Zz_2$$



Figure 4. 2: Point 1 represents the starting point of the cutting tool while point 2 represents its end point during rapid motion or linear interpolation.

The feedrate for the x, y and z axes during rapid motion is given by equations (4.17), (4.18) and (4.19) respectively. The overall rapid movement feedrate, f , is machine specific. In the Emco concept mill 55 CNC machine, the value of this feedrate is 2000 mm/min.

$$f_x = \left(\frac{x_d}{\sqrt{(x_d^2 + y_d^2 + z_d^2)}} \right) f \quad (4.17)$$

$$f_y = \left(\frac{y_d}{\sqrt{(x_d^2 + y_d^2 + z_d^2)}} \right) f \quad (4.18)$$

$$f_z = \left(\frac{z_d}{\sqrt{(x_d^2 + y_d^2 + z_d^2)}} \right) f \quad (4.19)$$

Where x_d , y_d , z_d are distances moved in the x-axis, y-axis and z-axis respectively. The distances moved in the x-axis x_d , y-axis y_d and z-axis z_d , between point 1 and point 2 shown in Figure 4. 2, are given by equations (4.20), (4.21) and (4.22) respectively.

$$x_d = |x_2 - x_1| \quad (4.20)$$

$$y_d = |y_2 - y_1| \quad (4.21)$$

$$z_d = |z_2 - z_1| \quad (4.22)$$

The straight-line distance from point 1 to point 2 is given by equation (4.23). Where d is the straight-line distance between point 1 and point 2.

$$d = \sqrt{x_d^2 + y_d^2 + z_d^2} \quad (4.23)$$

Edem & Mativenga (2017) presented a method for determining time to completed rapid motion for linear interpolation in machining. Their method accounted for time taken during acceleration phase of feed drive system and time taken at full feedrate speed. The method they employed, is used to determine machining time in this thesis. Using this method, the time required for motion of the feed drive system during rapid motion is given by equation (4.24).

$$t_{feed} = \begin{cases} 2t_a + \frac{d - 2d_a}{f} , for (d \geq 2d_a) \\ \sqrt{\frac{2t_a d}{f}} , for (d < 2d_a) \end{cases} \quad (4.24)$$

Where; t_{feed} is the time required to complete rapid movement, t_a is the time taken during the acceleration phase, d is the total travel distance, d_a is the distance moved by the feed axis during the acceleration phase. The acceleration time t_a and acceleration distance d_a are given by equation (4.25) and (4.26) respectively. Where a is the acceleration of the CNC machine feed drive system.

$$t_a = \frac{f}{a} \quad (4.25)$$

$$d_a = \frac{f^2}{2a} \quad (4.26)$$

Equation (4.16) is used to model the energy consumption for feed drive system in this thesis. In determining constants in equation (4.16), the experimental setup in chapter 3 is used to determine the relationship between power consumption and two variables; feedrate and weight of the workpiece. Figure 4. 3 shows the relationship between the power consumption and the feedrate, for the Emco concept mill 55 CNC machine, along the x and y axes.

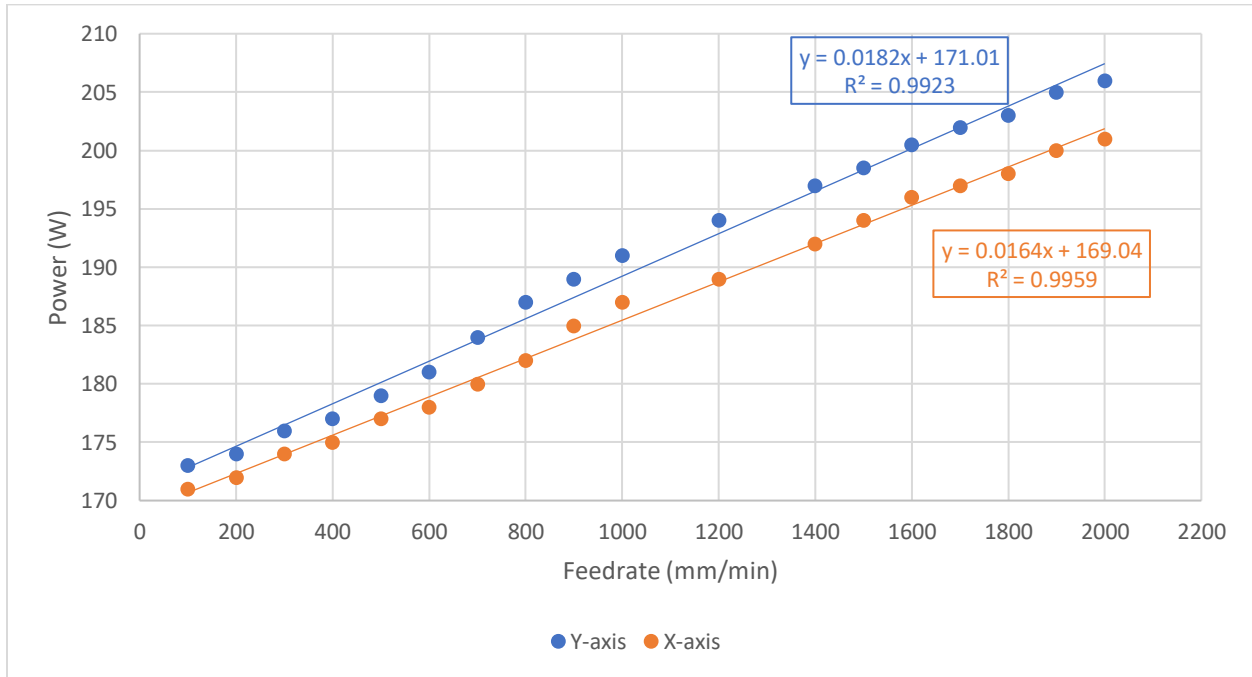


Figure 4. 3: The graph for power against feedrate, for both the x-axis and the y-axis.

Figure 4. 3 shows that using a linear equation to model power consumption of a CNC machine with respect to feedrate, gives a coefficient of determination, R^2 , greater than 0.99 for both x and y axes. Such high coefficients of determinations, result in high accuracy prediction of energy consumption. Figure 4. 3 further shows that power consumption along the y-axis is greater than power along the x-axis.

For the Emco concept mill 55 CNC machine, it was observed that the weight of the workpiece does not affect energy consumption. This was done by adding specified weights to the vice of the CNC machine and measuring power consumption for moving the feed axes with addition of weights. It was observed that this power consumption was equal to power consumption without the addition of weights. However, experiments by Edem & Mativenga (2016) on larger CNC machines revealed that addition of weights increases the energy consumption. They used weights up the weight of 8200 N. Results obtained for the the Emco concept mill 55 CNC machine is due to the fact that the the Emco concept mill 55 CNC machine only supports small weights, up to a mass of 10kg. Therefore, experiment in the the Emco concept mill 55 CNC machine was carried out with weights up to 100 N.

Figure 4. 4 shows the relationship between the power consumption and the feedrate, for the Emco concept mill 55 CNC machine, along the z-axis. In the Emco concept mill 55 CNC machine, the z-axis motion, moves the spindle in an upward and downward motion.

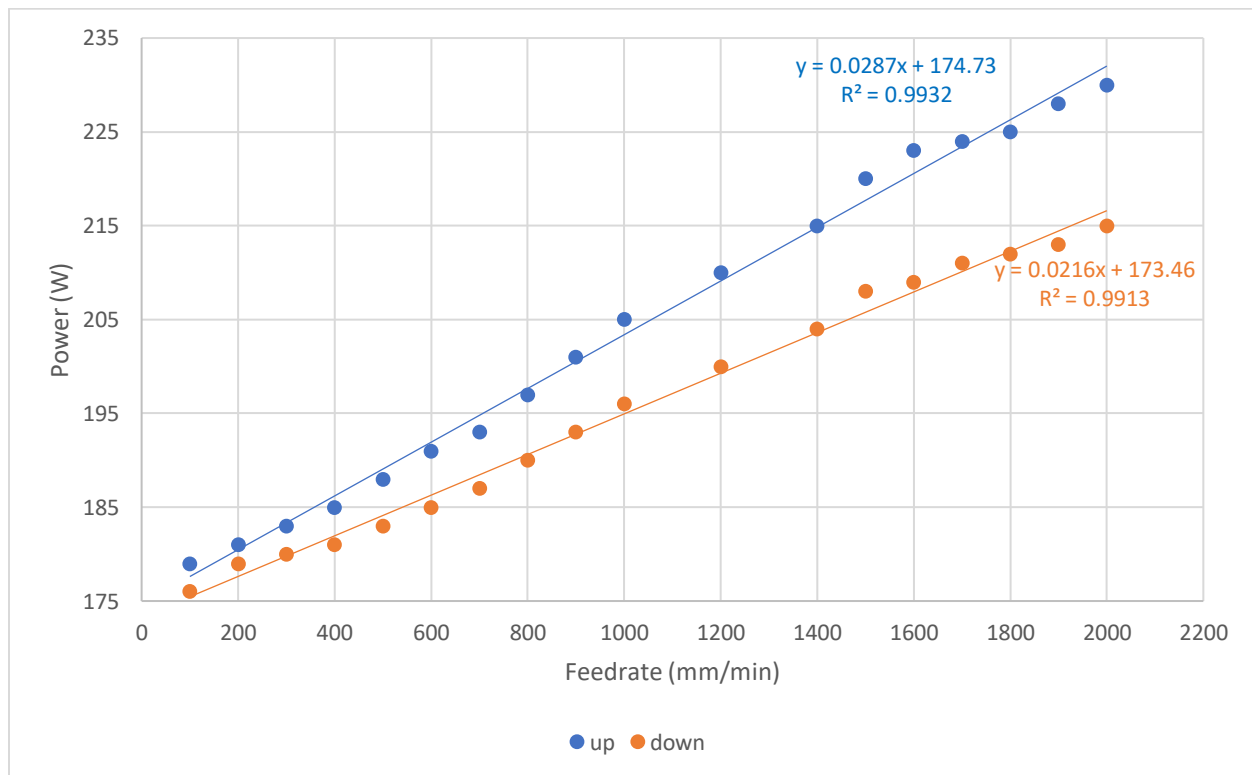


Figure 4. 4: The graph for power against feedrate, along the z-axis

The linear regression model used for power consumption along the z-axis also gives high coefficient of determination, R^2 , as shown in Figure 4. 4. The coefficient of determination is greater than 0.99, for both the upwards motion and downwards motion of the z-axis. Figure 4. 4 also shows that there is higher power consumption for upward motion than downward motion. This is because, for upward motion, the spindle is being moved against gravitation force, while for downward motion, the spindle is being moved along the gravitational force.

Linear regression equations shown in Figure 4. 3 and Figure 4. 4 are used to determine constants for the power consumption model of feed drive system, shown in equation (4.16). The fixed power consumption, which is 161 watts, is deducted from these equations. The resulting equations are then substituted to equation (4.16) to determine constants for feed drive system power model. Table 4. 1 shows constants for the feed axes power model.

Table 4. 1: Constants for the feed drive system power model

Constants	Value
c_x	0.0164
c_y	0.0182
c_z	0.0287
c_{-z}	0.0216
q_x	8.04
q_y	10.01
q_z	13.73
q_{-z}	12.46

The other remaining constants, for a_i and b_i , in the model are equal to zero. This is because, as per experimental results, the effect of weights in the Emco concept mill 55 CNC machine has demonstrated to be negligible.

4.2.5 Linear interpolation energy consumption

Linear interpolation energy consumption, E_{linear_int} , is given by equation (4.27). Where, P_{feed} is the mean power consumption for movement of the feed drive system, with t_{feed} as its corresponding time duration. P_{linear_cut} is the mean power consumption for material removal along the specified axis, with t_{linear_cut} being its corresponding time duration.

$$E_{linear_int} = P_{feed} * t_{feed} + P_{linear_cut} * t_{linear_cut} \quad (4.27)$$

P_{feed} and t_{feed} have already been dealt with in the previous section, section 4.2.4, on rapid movement energy consumption. The mean power consumption for linear cutting, P_{linear_cut} , has been observed to vary with respect to material removal rate (MRR) from the literature review of energy models, discussed in chapter 2. It has been observed that, in most research studies, this power consumption has been successfully modelled into linear regression model with respect to MRR (He et al., 2012; S. Pavanaskar & McMains, 2015; Sarikaya et al., 2022; Sihag & Sangwan, 2020). The mean power consumption model for linear cutting, P_{linear_cut} , presented in this thesis, also proposes a linear regression model with respect to MRR. This model is shown in equation

(4.28), where MRR_i is the material removal rate in a given axis, u_i and s_i , are constants to be determined experimentally for each respective axis.

$$P_{linear_cut} = \sum_{i=x,y,z,-z} u_i MRR_i + s_i \quad (4.28)$$

Summation of the power consumption due to movement of the feed drive system (P_{feed} , given by equation (4.16)) and power consumption due material removal (P_{linear_cut} , given by equation(4.28)), gives the total power consumption during linear interpolation P_{linear_int} , given by equation (4.29).

$$P_{linear_int} = \sum_{i=x,y,z,-z} (a_i W f_i + b_i W + c_i f_i + q_i) + \sum_{i=x,y,z,-z} u_i MRR_i + s_i \quad (4.29)$$

The linear interpolation cutting power state is activated by the G01 code. Figure 4. 2 shows schematic for a linear interpolation. Point 1 in Figure 4. 2 represents the starting point of the cutting tool while point 2 represents its end point in a given linear interpolation. Let x_1, y_1, z_1 represent the coordinates of the starting point while x_2, y_2, z_2 represents coordinates of the end point. The syntax for the G01 code is then given by:

$$G01 \ Xx_2 \ Yy_2 \ Zz_2 \ Ff$$

Where f is the feedrate.

MRR is a function of feedrate. MRR for cutting along the z-axis, MRR_z , is given by equation;

$$MRR_z = \frac{\pi D^2}{4} f_z \quad (4.30)$$

Where, D , is the diameter of the end mill, and f_z is the feedrate along the z-axis.

MRR in the x-axis direction, MRR_x , is given by equations (4.31). Where, d_c is depth of cut, w_x is width of cut in the x-axis direction and f_x is feedrate in the x-axis direction.

$$MRR_x = d_c w_x f_x \quad (4.31)$$

The magnitude of feedrate in the x-axis direction f_x , is given by equation (4.17). The width of cut in the y-axis direction, w_x , is given by equation (4.32). The width of cut, w , is given by the percentage stepover of the end mill cutter during cutting.

$$w_x = \frac{f_x}{f} w \quad (4.32)$$

MRR in the y-axis direction, MRR_y , is given by equations (4.33). Where, d_c is depth of cut, w_y is width of cut in the y-axis direction and f_y is feedrate in the y-axis direction.

$$MRR_y = d_c w_y f_y \quad (4.33)$$

The magnitude of feedrate in the y-axis direction, f_y , is given by equation (4.18). The width of cut in the y-axis direction, w_y , is given by equation (4.34).

$$w_y = \frac{f_y}{f} w \quad (4.34)$$

Figure 4. 5 shows the relationship between power consumption and MRR in the Emco concept mill 55 CNC machine, along the x and y axes. Figure 4. 5 shows that using a linear regression model to model power consumption of a CNC machine with respect to MRR, gives a coefficient of determination, R^2 , greater than 0.98 for both the x and the y axes. These coefficients of determinations were deemed high enough to produce highly accurate results in prediction of energy consumption. Figure 4. 5 further shows that power consumption for cutting along the y-axis is greater than power consumption for cutting along the x-axis.

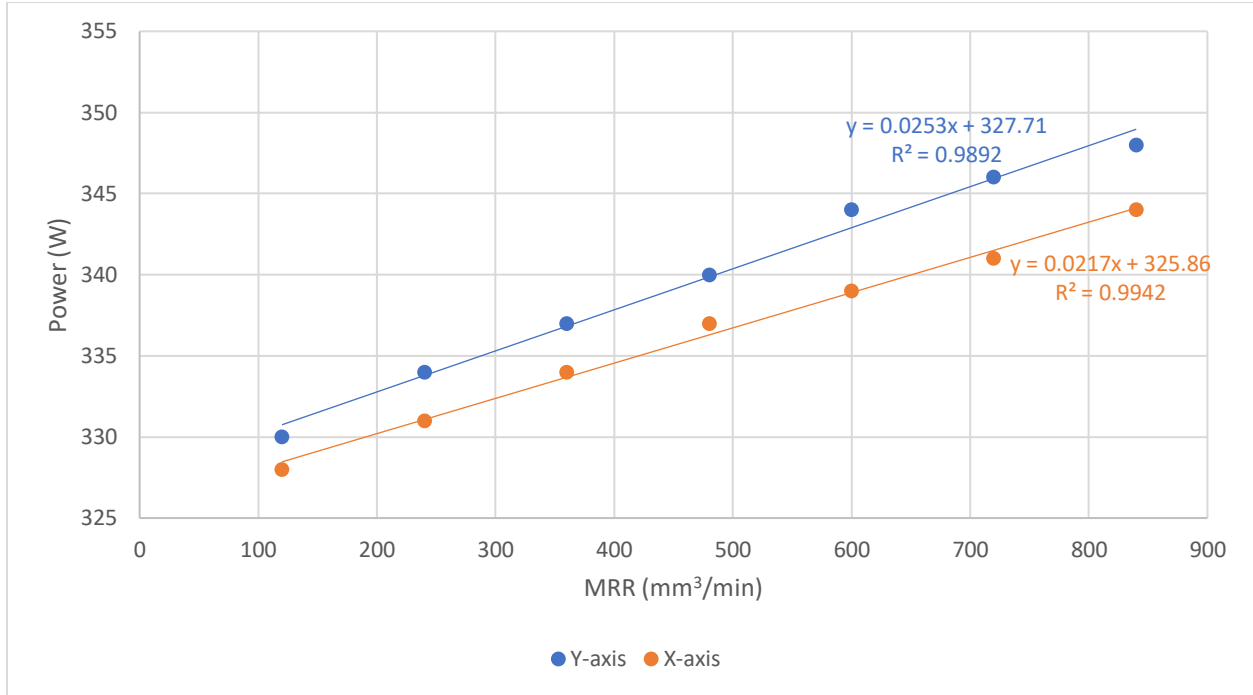


Figure 4. 5: The graph for power against MRR, for both the x-axis and the y-axis directions.

Figure 4. 6 shows the relationship between power consumption and MRR in the Emco concept mill 55 CNC machine, along the z-axis direction. Figure 4. 6 shows that using a linear regression model to model power consumption of a CNC machine with respect to MRR along the z-axis direction, gives a coefficient of determination, R^2 , greater than 0.99. This coefficient of determination was considered to be high enough to produce highly accurate results in prediction of energy consumption in CNC machining.

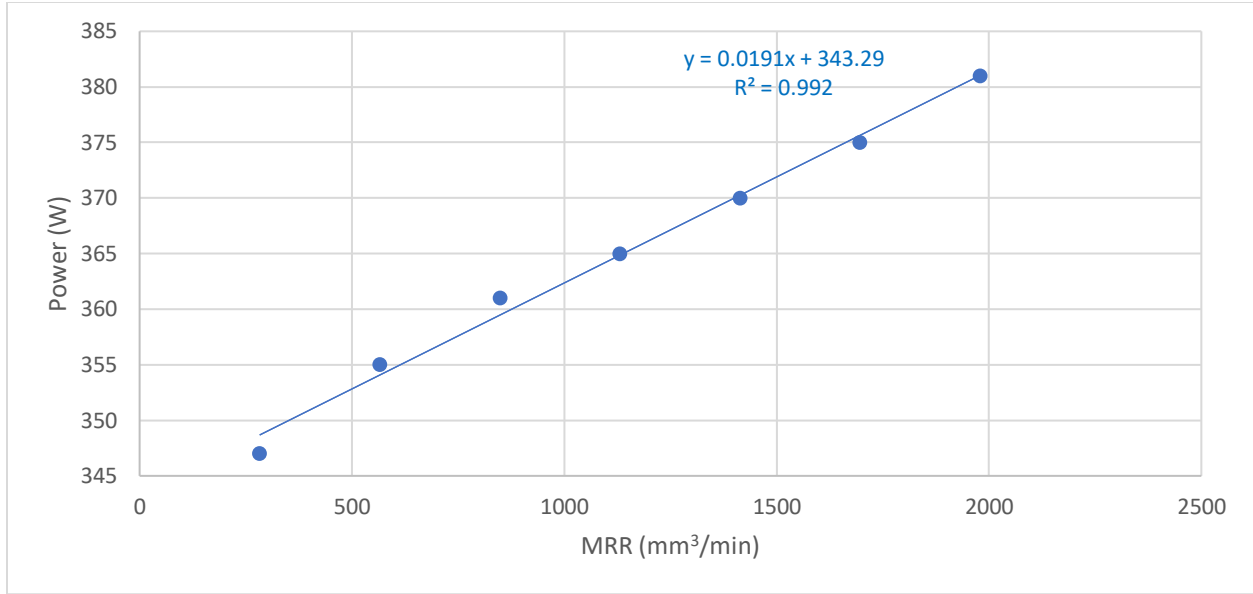


Figure 4. 6: The graph for power consumption against MRR along the z-axis direction

Linear regression equations shown in Figure 4. 5 and Figure 4. 6 are used to determine constants for the power consumption model for linear interpolation cutting, shown in equation (4.28). The fixed power, spindle power and feed power are deducted from linear regression equations shown in Figure 4. 5 and Figure 4. 6. The resulting equations are then substituted to equation (4.28) to determine constants for linear interpolation power model. Table 4. 2 shows constants for linear interpolation power model.

Table 4. 2: Constants for linear interpolation power model.

Constants	Value
u_x	0.0207
u_y	0.0243
u_{-z}	0.0181
s_x	44.12
s_y	44.00
s_{-z}	57.13

4.2.6 Circular interpolation energy consumption

Circular interpolation energy consumption, $E_{circular_int}$, is given by equation (4.35). Where, $P_{circular_feed}$ is the mean power consumption for movement of the feed drive system during circular interpolation, with $t_{circular_feed}$ being its corresponding time duration. $P_{circular_cut}$ is the mean power consumption for material removal during circular interpolation, with $t_{circular_cut}$ being its corresponding time duration.

$$E_{circular_int} = P_{circular_feed} * t_{circular_feed} + P_{circular_cut} * t_{circular_cut} \quad (4.35)$$

From equation (4.35), it can be observed that circular interpolation energy consumption is given by the summation of power consumption for movement of the feed drive system and power consumption for material removal during circular interpolation. Section 4.2.6.1 deals with power consumption for movement of the feed drive system during circular interpolation while section 4.2.6.2 deals with power consumption for material removal during circular interpolation. Section 4.2.6.3 discusses the overall circular interpolation energy consumption model.

4.2.6.1 Movement of feed drive system energy consumption

To produce a model for energy consumption due to movement of the feed drive system during circular interpolation, a method for evaluating feedrate in the x-axis direction and in the y-axis direction at all points around the circular interpolation arc should be derived. This is done by analyzing the circular interpolation geometry as shown in Figure 4. 7.

Figure 4. 7 shows how feedrate varies with respect to circular interpolation angle θ during circular interpolation. The overall feedrate f changes in direction during circular interpolation as shown in Figure 4. 7, but its magnitude remains constant. The magnitude of feedrate in the x-axis direction and the in the y-axis direction varies with respect to the value of θ , which is measured from the positive x-axis, as is shown in Figure 4. 7. The magnitude of feedrate in the x-axis direction, f_x , and in the y-axis direction, f_y , during circular interpolation is given by equations (4.36) and (4.37) respectively. Figure 4. 7 shows feedrates in the first quadrant only, however, analysis and equations on feedrates discussed in this chapter apply to all the four quadrants.

$$f_x = f|\sin \theta| \quad (4.36)$$

$$f_y = f|\cos \theta| \quad (4.37)$$

Time taken during circular interpolation is given by equation (4.38). Where t is the time taken to complete a given circular interpolation, f is the feedrate, θ is the circular interpolation angle measured as shown in Figure 4. 7, R is the radius of the circular interpolation arc, l is the length of the circular interpolation arc.

$$\begin{aligned} t &= \frac{l}{f} \\ &= \frac{\theta R}{f} \end{aligned} \quad (4.38)$$

For small angular increment $d\theta$, the corresponding incremental time duration dt , is given by equation (4.39).

$$dt = \frac{R}{f} d\theta \quad (4.39)$$

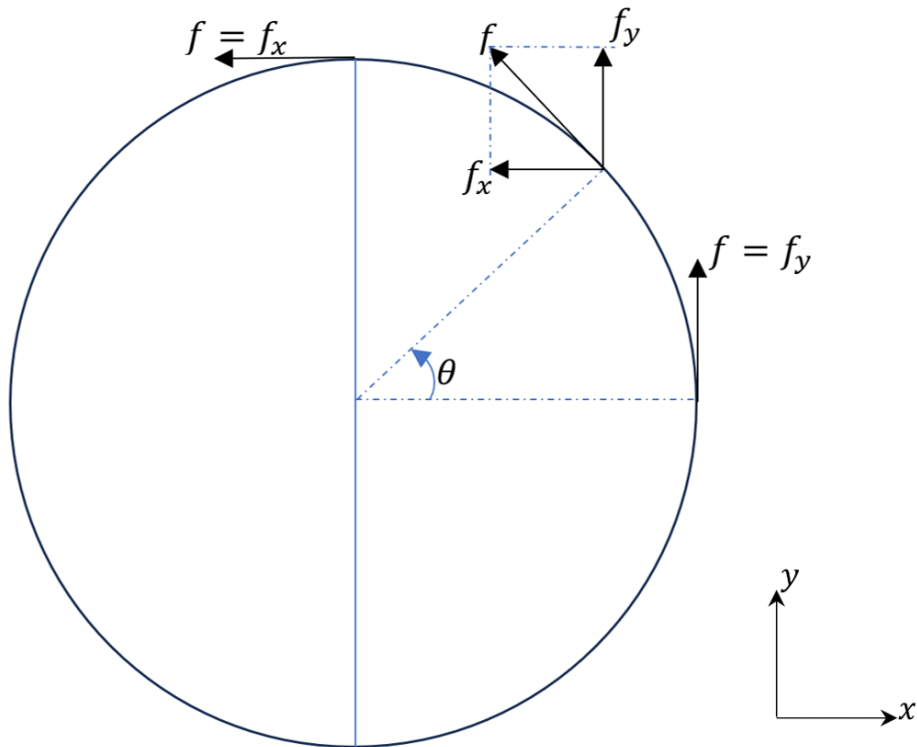


Figure 4. 7: Shows how feedrate varies during circular interpolation.

Equation (4.16) gives power consumption for moving the feed drive system during linear motion. For computing power consumption for moving the feed drive system in the x-axis direction during circular interpolation $P_{feed_{cx}}$, equation (4.36) is substituted into equation (4.16), giving equation (4.40).

$$P_{feed_{cx}} = (a_x W + c_x)(f|\sin \theta|) + b_x W + q_x \quad (4.40)$$

Equation has an additional new variable, θ , which is the circular interpolation angle. This angle is measured from positive x-axis as shown in Figure 4. 7 and Figure 4. 8. Point 1 in Figure 4. 8 represents the starting point for circular interpolation having coordinates (x_1, y_1) and starting angle of circular interpolation θ , as θ_1 . The end point for circular interpolation is represented by point 2 having (x_2, y_2) as its coordinates, and end point angle of circular interpolation as θ_2 .

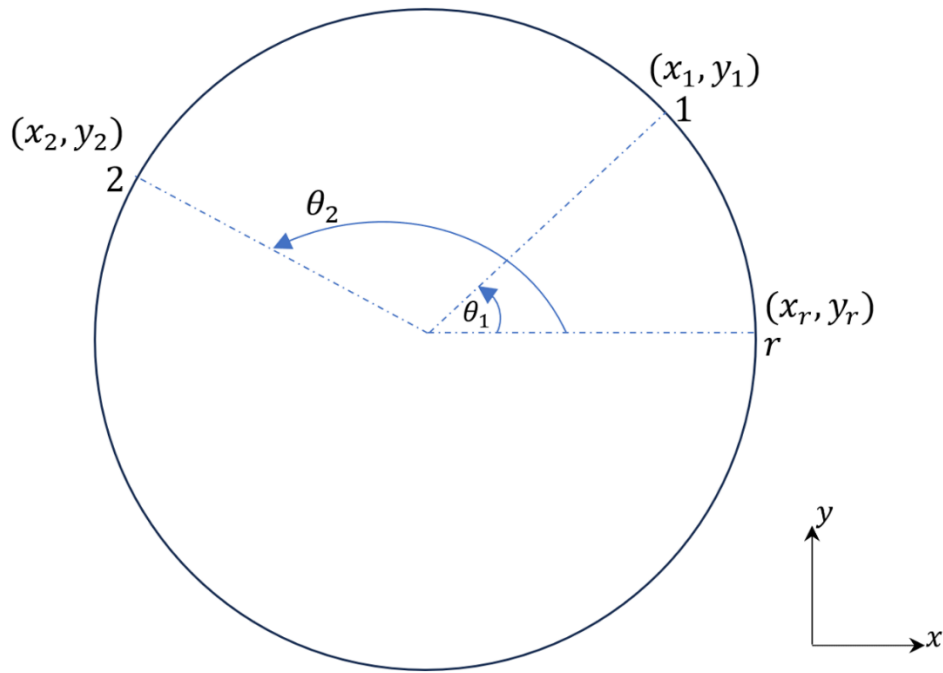


Figure 4. 8: A schematic of circular interpolation from point 1 to point 2

Halinga et al. (2023) revealed that the energy consumption for a linear segment in CNC machining is given by equation (4.41).

$$E = \int_{t_1}^{t_2} (|P_x(t)| + |P_y(t)|) dt \quad (4.41)$$

Where, E , is the total energy consumption for the feed drive system, t_1 and t_2 are the initial and final time for machining a linear segment, respectively. $P_x(t)$ and $P_y(t)$ are the feed drive power consumption values at a given time t , for the x-axis and y-axis directions, respectively.

The approach used by Halinga et al. (2023) in determining energy consumption for linear segments will be used in deriving the energy consumption model during circular interpolation, as circular interpolation is made of small linear segments. During circular interpolation both axes, x-axis and y-axis, are continuously moving simultaneously at varying feedrates. To compute energy consumption for moving the feed drive system in the x-axis direction, equation (4.42) is employed. Where E_{feed_cx} is the total energy consumption for moving the feed drive system in the x-axis direction during circular interpolation, P_{feed_cx} is the power consumption for moving the feed drive system in the x-axis direction during circular interpolation, t_1 is the time at the start of circular interpolation at point 1 as shown in Figure 4. 8. t_2 is time at the end of circular interpolation shown at point 2 in Figure 4. 8.

$$E_{feed_cx} = \int_{t_1}^{t_2} P_{feed_cx} dt \quad (4.42)$$

Substituting equations (4.39) and (4.40) into equation (4.42) gives equation

(4.43), which gives total energy consumption from the starting point angle θ_1 to the final interpolation angle θ_2 .

$$\begin{aligned} E_{feed_cx} &= \int_{\theta_1}^{\theta_2} \left[R(a_x W + c_x)(f|\sin \theta|) + \frac{R}{f}(b_x W + q_x) \right] d\theta \\ &= \frac{(\theta_2 + \theta_1)R}{f} (b_x W + q_x) + r(a_x W + c_x) \int_{\theta_1}^{\theta_2} |\sin \theta| d\theta \end{aligned} \quad (4.43)$$

Applying the mean value theorem to equation (4.42) gives the mean power consumption for moving the feed drive system in the x-axis direction, as shown in equation (4.44). Where P_{mfeed_cx} is the mean power consumption for moving the feed drive system in the x-axis direction during circular interpolation.

$$\begin{aligned} P_{mfeed_cx} &= \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} P_{feed_cx} dt \\ &= \frac{1}{t_2 - t_1} E_{feed_cx} \end{aligned} \quad (4.44)$$

The expression for E_{feed_cx} is given by equation

(4.43). The expression for $t_2 - t_1$ is given by integrating equation (4.39) over the interval t_1 to t_2 , giving equation (4.45).

$$t_2 - t_1 = \frac{R}{f} (\theta_2 - \theta_1) \quad (4.45)$$

Substituting equations

(4.43) and (4.45) into equation (4.44) gives equation (4.46). This equation gives the power consumption for moving the feed drive system in the x-axis direction during circular interpolation.

$$P_{mfeed_cx} = (b_x W + q_x) + \frac{(a_x W + c_x)f}{(\theta_2 - \theta_1)} \int_{\theta_1}^{\theta_2} |\sin \theta| d\theta \quad (4.46)$$

In the same way as in deriving the expression for power consumption for moving the feed drive system in the x-axis direction during circular interpolation (P_{mfeed_cx}), the mean power consumption expression for moving the feed drive system in the y-axis direction during circular interpolation (P_{mfeed_cy}), can be shown to be given by equation (4.47).

$$P_{mfeed_cy} = (b_y W + q_y) + \frac{(a_y W + c_y)f}{(\theta_2 - \theta_1)} \int_{\theta_1}^{\theta_2} |\cos \theta| d\theta \quad (4.47)$$

To obtain the equation for the total mean power consumption for moving the feed drive system during circular interpolation $P_{circular_feed}$, the mean power consumption for moving the feed drive system in the x-axis direction is added to the mean power consumption for moving the feed drive system in the y-axis direction. This result is given by equation (4.48).

$$\begin{aligned} P_{circular_feed} &= P_{mfeed_cx} + P_{mfeed_cy} \\ &= \sum_{i=x,y} (b_i W + q_i) + \frac{(a_x W + c_x)f}{(\theta_2 - \theta_1)} \int_{\theta_1}^{\theta_2} |\sin \theta| d\theta \\ &\quad + \frac{(a_y W + c_y)f}{(\theta_2 - \theta_1)} \int_{\theta_1}^{\theta_2} |\cos \theta| d\theta \end{aligned} \quad (4.48)$$

4.2.6.2 Material removal energy consumption

To produce a model for energy consumption due to material removal during circular interpolation, cutting power in the x-axis direction and y-axis direction should be analyzed and be computed separately. The sum of cutting power in these two axes, gives the total cutting power during circular interpolation.

As in linear interpolation, the cutting power in circular interpolation is also modeled to be proportional to MRR as shown in equation (4.28). By first considering cutting power in the x-axis direction, the x-axis cutting power in circular interpolation is given by equation (4.49). where P_{cut_cx} is the cutting power consumption in the x-axis direction during circular interpolation, MRR_x is material removal in the x-axis direction, u_x and s_x are constants to be determined experimentally, d_c is the depth of cut, w_x is width of cut in the x-axis direction and f_x is feedrate in the x-axis direction.

$$\begin{aligned} P_{cut_cx} &= u_x MRR_x + s_x \\ &= u_x d_c w_x f_x + s_x \end{aligned} \quad (4.49)$$

The width of cut in the x-axis direction, w_x , and in the y-axis direction, w_y , is given by equations (4.50) and (4.51) respectively. Where w is the width of cut. The width of cut, w , is given by the percentage stepover of the cutting tool during machining.

$$w_x = w|\sin \theta| \quad (4.50)$$

$$w_y = w|\cos \theta| \quad (4.51)$$

To compute power consumption for cutting in the x-axis direction at specified points around the circular interpolation arc, equations (4.36) and (4.50) are substituted into equation (4.49), giving equation (4.52).

$$P_{cut_cx} = u_x d_c w f \sin^2 \theta + s_x \quad (4.52)$$

The total energy consumption for cutting in the x-axis direction during circular interpolation E_{cut_cx} , is given by equation (4.53).

$$E_{cut_cx} = \int_{t_1}^{t_2} P_{cut_cx} dt \quad (4.53)$$

Equations (4.52) and (4.39) are then substituted into equation (4.53), giving equation (4.54). This equation computes the cutting energy consumption from the starting point angle θ_1 to the final interpolation angle θ_2 . Angular parameters θ_1 and θ_2 are as shown in Figure 4. 8.

$$E_{cut_cx} = \int_{\theta_1}^{\theta_2} \left(u_x d_c w R \sin^2 \theta + \frac{R}{f} s_x \right) d\theta \quad (4.54)$$

$$= u_x d_c w R \left[\frac{\theta_2 - \theta_1}{2} - \frac{\sin 2\theta_2 - \sin 2\theta_1}{4} \right] + \frac{R s_x}{f} (\theta_2 - \theta_1)$$

Equation (4.53) gives the total energy required for cutting in the x-axis direction during circular interpolation. Applying the mean value theorem to equation (4.53) gives the mean power consumption for cutting in the x-axis direction during circular interpolation, given by equation (4.55). Where P_{mcut_cx} is the mean power consumption for cutting in the x-axis direction during circular interpolation.

$$\begin{aligned} P_{mcut_cx} &= \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} P_{cut_cx} dt \\ &= \frac{1}{t_2 - t_1} E_{cut_cx} \end{aligned} \quad (4.55)$$

The expression for E_{cut_cx} is given by equation (4.54) and the expression for $t_2 - t_1$ is given by equation (4.45). Substituting equations (4.45) and (4.54) into equation (4.55) gives equation (4.56). This equation gives the power consumption for cutting in the x-axis direction during circular interpolation.

$$P_{mcut_cx} = \frac{u_x d_c w f}{\theta_2 - \theta_1} \left[\frac{\theta_2 - \theta_1}{2} - \frac{\sin 2\theta_2 - \sin 2\theta_1}{4} \right] + s_x \quad (4.56)$$

In the same way as in deriving the mean power consumption for cutting in the x-axis direction during circular interpolation (P_{mcut_cx}), it can be shown that the mean power consumption for cutting in the y-axis direction during circular interpolation (P_{mcut_cy}) is given by equation (4.57).

$$P_{mcut_cy} = \frac{u_y d_c w f}{\theta_2 - \theta_1} \left[\frac{\theta_2 - \theta_1}{2} + \frac{\sin 2\theta_2 - \sin 2\theta_1}{4} \right] + s_y \quad (4.57)$$

The mean power consumption for cutting during circular interpolation $P_{circular_cut}$, in x-y plane is given by summation of equations (4.56) and (4.57). The result is shown in equation (4.58).

$$P_{circular_cut} = \frac{u_x d_c w f}{\theta_2 - \theta_1} \left[\frac{\theta_2 - \theta_1}{2} - \frac{\sin 2\theta_2 - \sin 2\theta_1}{4} \right] + \frac{u_y d_c w f}{\theta_2 - \theta_1} \left[\frac{\theta_2 - \theta_1}{2} + \frac{\sin 2\theta_2 - \sin 2\theta_1}{4} \right] + \sum_{i=x,y} s_i \quad (4.58)$$

4.2.6.3 Circular interpolation energy consumption model

The total circular interpolation energy consumption, $E_{circular_int}$, is given by equation (4.35). This equation can be rewritten in the form shown by equation (4.59). Where $P_{circular_int}$ is the mean power consumption for circular interpolation, $t_{circular_int}$ is the time taken to complete the circular interpolation.

$$E_{circular_int} = P_{circular_int} * t_{circular_int} \quad (4.59)$$

$P_{circular_int}$ is given by equation (4.60) while $t_{circular_int}$ is given by equation (4.45).

$$P_{circular_int} = P_{circular_feed} + P_{circular_cut} \quad (4.60)$$

As shown by equation (4.60), the mean power consumption for circular interpolation $P_{circular_int}$, is given by summation of; mean power consumption due to movement of the feed drive system, $P_{circular_feed}$, and the cutting power consumption, $P_{circular_cut}$, during circular interpolation. This result is given by the summation of equations (4.48) and (4.58), giving in equation

(4.61). The value of constants in this equation is given by Table 4. 1 and Table 4. 2.

$$\begin{aligned}
P_{circular_int} = & \sum_{i=x,y} (b_i W + q_i + s_i) + \frac{(a_x W + c_x) f}{(\theta_2 - \theta_1)} \int_{\theta_1}^{\theta_2} |\sin \theta| d\theta \\
& + \frac{(a_y W + c_y) f}{(\theta_2 - \theta_1)} \int_{\theta_1}^{\theta_2} |\cos \theta| d\theta \\
& + \frac{u_x d_c w f}{\theta_2 - \theta_1} \left[\frac{\theta_2 - \theta_1}{2} - \frac{\sin 2\theta_2 - \sin 2\theta_1}{4} \right] \\
& + \frac{u_y d_c w f}{\theta_2 - \theta_1} \left[\frac{\theta_2 - \theta_1}{2} + \frac{\sin 2\theta_2 - \sin 2\theta_1}{4} \right]
\end{aligned} \tag{4.61}$$

The mean power consumption for circular interpolation $P_{circular_int}$, given by equation (4.61), is a function the starting angle of circular interpolation, θ_1 , and the final angle of circular interpolation, θ_2 . These two angles are as shown in Figure 4. 8. The two angles are evaluated using information extracted from the NC. The G-code for circular interpolation is given by two codes; G02 for clockwise circular interpolation and G03 for counter-clockwise circular interpolation, shown in Figure 4. 9.

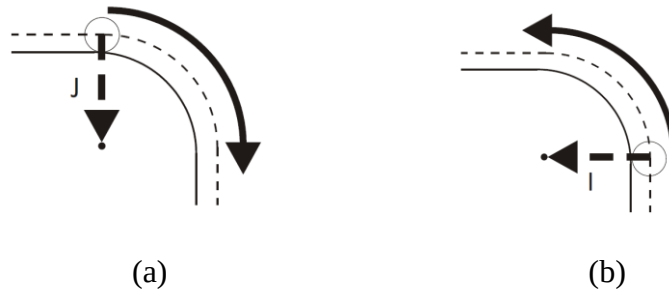


Figure 4. 9: (a) G02, clockwise circular interpolation. (b) G03, counterclockwise circular interpolation. (Autodesk, 2014)

The NC code syntax for the two circular interpolation code is as shown below:

G02 X x_2 Y y_2 I I J J F f

G03 X x_2 Y y_2 I I J J F f

Where x_2 and y_2 are the end points for circular interpolation as shown in Figure 4. 8. I and J , are displacements to the center of the circular interpolation arc, in the x-axis and y-axis directions respectively, as shown in Figure 4. 9 and f is the feedrate.

In deriving the values for θ_1 and θ_2 , the radius of the circular interpolation arc, R , is first evaluated using equation (4.62). Where I and J , are displacements to the center of the circular interpolation arc, in the x-axis and y-axis directions respectively.

$$R = \sqrt{I^2 + J^2} \quad (4.62)$$

The reference point coordinates x_r and y_r , are then determined using equations (4.63) and (4.64) respectively. Where x_1 and y_1 are the starting points for circular interpolation as shown in Figure 4. 8.

$$x_r = x_1 + I + R \quad (4.63)$$

$$y_r = y_1 + J \quad (4.64)$$

Next, the distance between reference point and point 1, l_1 , is determined as shown in equation (4.65). The distance between reference point and point 2, l_2 , is determined as shown in equation (4.66). The reference point, point 1 and point 2 are as shown in Figure 4. 8.

$$l_1 = \sqrt{(x_1 - x_r)^2 + (y_1 - y_r)^2} \quad (4.65)$$

$$l_2 = \sqrt{(x_2 - x_r)^2 + (y_2 - y_r)^2} \quad (4.66)$$

By applying the cosine rule, the angle θ_1 is then determined using equating (4.67), for counter-clockwise circular interpolation.

$$\theta_1 = \begin{cases} \cos^{-1}\left(1 - \frac{l_1^2}{2R^2}\right), \text{for } y_1 \geq y_r \\ 2\pi - \cos^{-1}\left(1 - \frac{l_1^2}{2R^2}\right), \text{for } y_1 < y_r \end{cases} \quad (4.67)$$

For clockwise circular interpolation, angle θ_1 , is given by equation (4.68).

$$\theta_1 = \begin{cases} \cos^{-1}\left(1 - \frac{l_1^2}{2R^2}\right), \text{for } y_1 \leq y_r \\ 2\pi - \cos^{-1}\left(1 - \frac{l_1^2}{2R^2}\right), \text{for } y_1 > y_r \end{cases} \quad (4.68)$$

To determine the angle θ_2 , an intermediary angle θ'_2 is first determined using equation (4.69), for counter-clockwise circular interpolation.

.

$$\theta'_2 = \begin{cases} \cos^{-1}\left(1 - \frac{l_2^2}{2R^2}\right), \text{for } y_2 \geq y_r \\ 2\pi - \cos^{-1}\left(1 - \frac{l_2^2}{2R^2}\right), \text{for } y_2 < y_r \end{cases} \quad (4.69)$$

For clockwise circular interpolation, the intermediary angle θ'_2 is determined using equation (4.70), for counter-clockwise circular interpolation.

$$\theta'_2 = \begin{cases} \cos^{-1}\left(1 - \frac{l_2^2}{2R^2}\right), & \text{for } y_2 \leq y_r \\ 2\pi - \cos^{-1}\left(1 - \frac{l_2^2}{2R^2}\right), & \text{for } y_2 > y_r \end{cases} \quad (4.70)$$

The angle θ_2 , is then determined using equation (4.71), for both clockwise and counter-clockwise circular interpolation.

$$\theta_2 = \begin{cases} \theta'_2 & \text{for } \theta_1 < \theta'_2 \\ \theta'_2 + 2\pi & \text{for } \theta_1 \geq \theta'_2 \end{cases} \quad (4.71)$$

4.2.7 Tool change energy

The process of automatic tool change is initiated by rapid movement of the spindle to a position designed for tool change. The tool magazine is then moved to the spindle to remove the endmill cutter from the spindle and then insert the required endmill cutter. Figure 4. 10 shows the tool magazine with the spindle in the ready position for tool change in the Emco concept mill 55 CNC machine.



(a)



(b)

Figure 4. 10: the tool magazine with the spindle in the ready position for tool change in the Emco concept mill 55 CNC machine.

To determine energy consumption for tool change E_{tool_change} , the power consumption for the tool magazine actuation system will have to be determined. Thereafter, the time to reach each station in the tool magazine will have to be determined as well. Having the power consumption of the tool magazine actuation system and the time to reach each tool station in the tool magazine, the tool change energy consumption can be determined using equation (4.72). Where $P_{tool_magazine}$ is the power consumption of the tool magazine actuation system, $t_{tool_magazine}$ is the time duration for which the tool magazine actuations system is activated. Equation (4.72) includes the energy required for feed drive system movement, which accounts for energy required to position the spindle to the appropriate position designed for tool change. The feed drive system motion energy is determined as described in section 4.2.4, the section on rapid movement energy consumption.

$$E_{tool_change} = P_{feed} * t_{feed} + P_{tool_magazine} * t_{tool_magazine} \quad (4.72)$$

In the Emco concept mill 55 CNC machine, the motion of the tool magazine is actuated by an electric motor, and the measured power consumption of the motor during actuating was 205 Watts. The tool magazine of the Emco concept mill 55 CNC machine has seven stations. The measured average time to move from one station to another was 0.2 seconds.

4.3 Complete CNC energy consumption model

The energy consumption for each block of NC in CNC machining is given by equation (4.2). The expressions for the seven energy divisions; E_{fixed} , $E_{coolant_pump}$, $E_{spindle}$, E_{rapid} , E_{linear_int} , $E_{circular_int}$ and E_{tool_change} are substituted into equation (4.2), giving equation (4.73). Expression for the seven energy divisions in CNC energy consumption are discussed throughout section 4.2. Equation (4.73) is an energy consumption model which can be used for all three axis CNC machines. Once constants for a particular CNC machine are substituted into equation (4.73), this equation then becomes a specific energy model for that particular CNC machine.

$$\begin{aligned}
E_{block} = & P_{fixed} * t_{fixed} + P_{coolant_pump} * t_{coolant_pump} + (mN + k) \\
& * t_{spindle} + t_{feed} \sum_{i=x,y,z,-z} (a_i W f_i + b_i W + c_i f_i + q_i) \\
& + t_{linear_int} \sum_{i=x,y,z,-z} (u_i MRR_i + s_i) \\
& + t_{circular_int} \sum_{i=x,y} (b_i W + q_i + s_i) \\
& + \frac{(a_x W + c_x) f}{(\theta_2 - \theta_1)} \int_{\theta_1}^{\theta_2} |\sin \theta| d\theta + \frac{(a_y W + c_y) f}{(\theta_2 - \theta_1)} \int_{\theta_1}^{\theta_2} |\cos \theta| d\theta \\
& + \frac{u_x d_c w f}{\theta_2 - \theta_1} \left[\frac{\theta_2 - \theta_1}{2} - \frac{\sin 2\theta_2 - \sin 2\theta_1}{4} \right] \\
& + \frac{u_y d_c w f}{\theta_2 - \theta_1} \left[\frac{\theta_2 - \theta_1}{2} + \frac{\sin 2\theta_2 - \sin 2\theta_1}{4} \right] \\
& + (P_{tool_magazine} * t_{tool_magazine})
\end{aligned} \tag{4.73}$$

The time duration for the each of the power states in equation (4.73) is given by equation (4.24) or equation (4.38), depending on the on the NC. For G00 and G01 codes, equation (4.24) is utilized to compute time duration for the given power state. For G02 and G03 codes, equation (4.38) is utilized to compute time duration for the given power state. This allows for energy consumption for each block of NC to be expressed as shown in equation (4.74). Where P_{block} is the mean power to be consumed by a block of NC, while t_{block} is its time duration. This equation was used by Pavanaskar & McMains (2015) to compute energy consumption in CNC machining.

$$E_{block} = P_{block} * t_{block} \tag{4.74}$$

Where, t_{block} is given by equation (4.24) for G00 and G01 codes while for G02 and G03 codes, t_{block} is given by equation (4.38). The power for each block of NC P_{block} is given by equation (4.75).

$$\begin{aligned}
P_{block} = & P_{fixed} + P_{coolant_pump} + (mN + k) \\
& + \sum_{i=x,y,z,-z} (a_i W f_i + b_i W + c_i f_i + q_i) \\
& + \sum_{i=x,y,z,-z} (u_i MRR_i + s_i) + \sum_{i=x,y} (b_i W + q_i + s_i) \\
& + \frac{(a_x W + c_x) f}{(\theta_2 - \theta_1)} \int_{\theta_1}^{\theta_2} |\sin \theta| d\theta + \frac{(a_y W + c_y) f}{(\theta_2 - \theta_1)} \int_{\theta_1}^{\theta_2} |\cos \theta| d\theta \\
& + \frac{u_x d_c w f}{\theta_2 - \theta_1} \left[\frac{\theta_2 - \theta_1}{2} - \frac{\sin 2\theta_2 - \sin 2\theta_1}{4} \right] \\
& + \frac{u_y d_c w f}{\theta_2 - \theta_1} \left[\frac{\theta_2 - \theta_1}{2} + \frac{\sin 2\theta_2 - \sin 2\theta_1}{4} \right] + P_{tool_magazine} \quad (4.75)
\end{aligned}$$

4.4 Conclusion

The energy consumption model developed in this thesis predicts total energy to be consumed by a CNC machine during machining. This model can be used for any geometry to be machined on any three axis CNC machine. The novelty of this energy model lies in the fact that it has been able to split material removal energy consumption into; linear interpolation energy consumption and circular interpolation energy consumption. With this novelty, detailed method for determining circular interpolation energy consumption directly from the NC was developed. The energy model also considers the weight of the work piece without requiring knowledge of weight of the vice and weight of feed drive system.

The input to CNC energy consumption model is the NC and the output is energy consumption. Considering the fact that CNC programs have multiple line of NC codes, it is not practical to compute energy consumption in CNC machining manually. To solve this problem, an energy analyzer software has been developed in this research. The next chapter presents the design of the CNC energy analyzer software. This software utilizes the CNC energy consumption model to compute energy consumption of various NC programs. The software then highlights the NC program having the least energy consumption.

Chapter 5: CNC ENERGY ANALYZER SOFTWARE DESIGN

5.1 Introduction

Manual calculations of energy consumption using the CNC energy consumption model developed in this thesis would be a tedious and long process, as the NC program usually contains numerous blocks/lines of code. To solve this problem, a software is developed to do all these calculations.

Some of the researchers who developed energy consumption models for CNC machines went on further to develop software to compute energy to be consumed by the CNC machine. These software have some limitation which will be addressed in this chapter. Accuracy and user-friendliness of these software are some of the limitations which will be dealt with in this chapter.

5.2 Software design

Python programming language was used to develop the energy software for this research. Tkinter package was used to create the graphical user interface (GUI) for the software. The GUI for this software is as shown in Figure 5. 1. The software has input parameters as shown in Figure 5. 1. These are entered to specify machining parameters. For input boxes which have the drop-down buttons, their specifications are selected from the database.

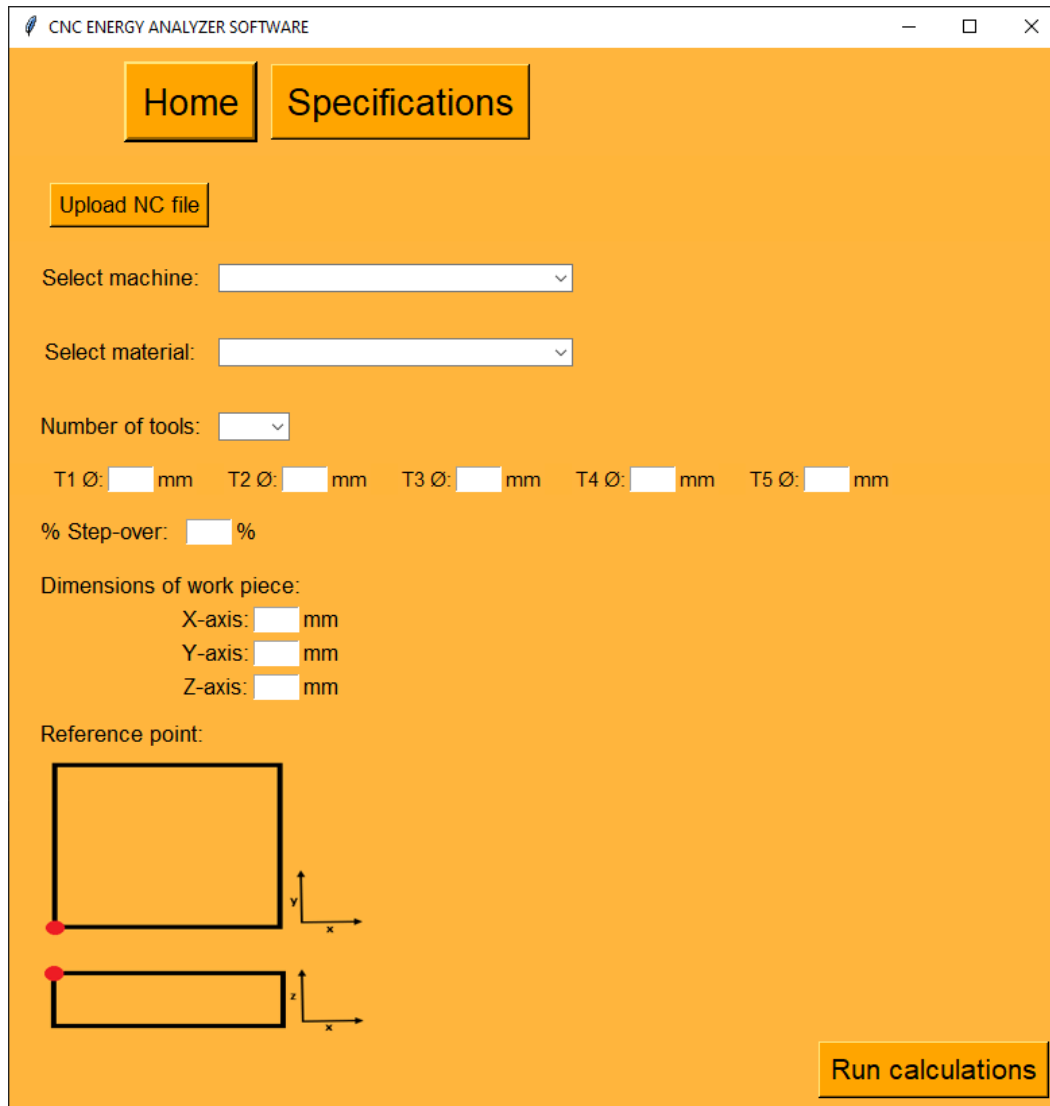


Figure 5. 1: GUI of the CNC energy software developed (Home page)

Once the ‘Upload NC file’ button is clicked, the windows dialog box pops up. From this dialog box, NC files can be selected. More than one NC file can be selected, which is a feature not supported by other software discussed in chapter 2. After selecting an NC file, the ‘Run calculations’ button can be clicked. Once this button is clicked the software computes the energy consumption for each NC file, using the algorithm shown in Figure 5. 2. Using this algorithm, each block of the NC program is passed through the CNC energy consumption model, and the resulting energies are added up to obtain the total energy to be consumed by each NC program during machining.

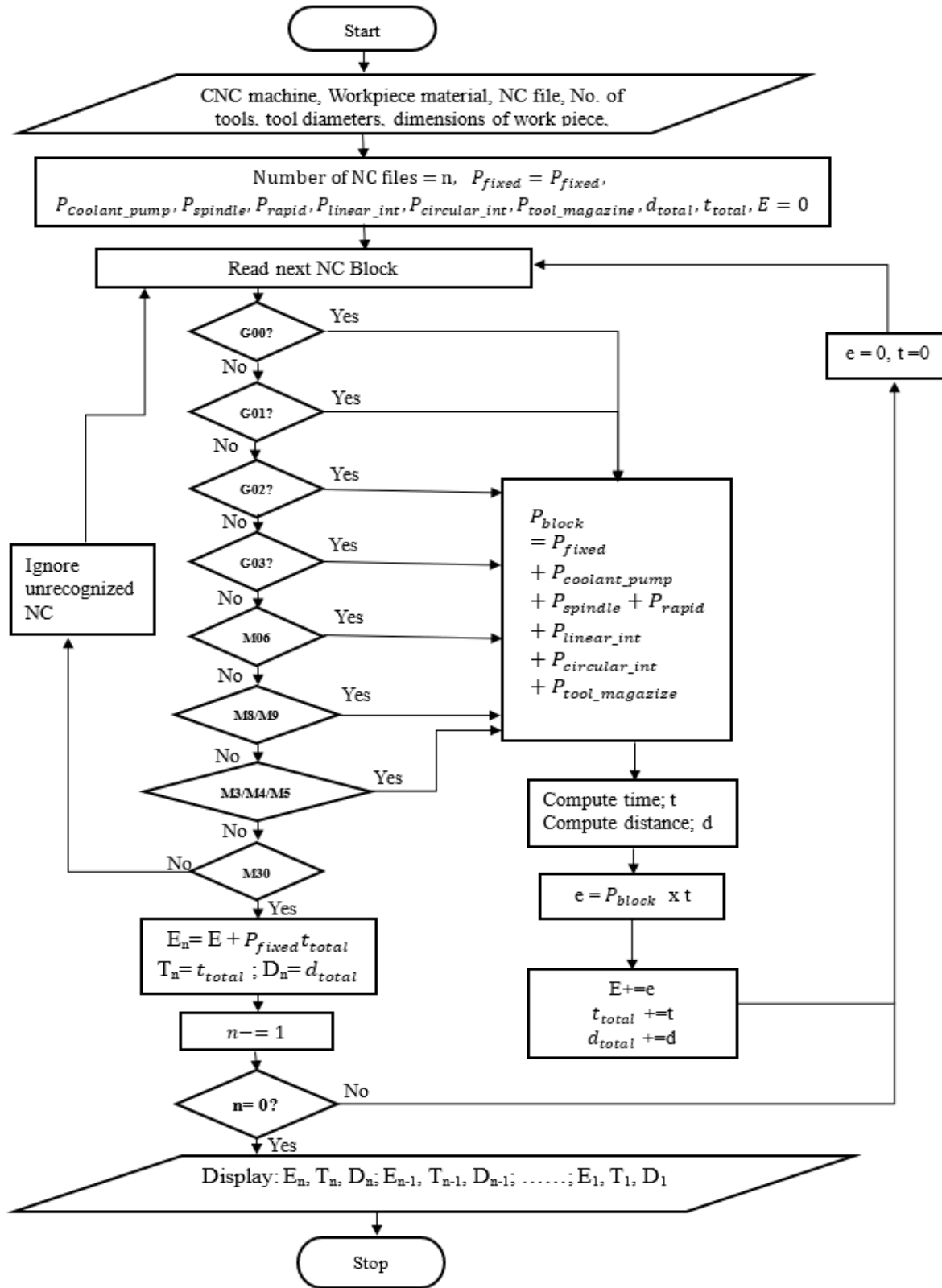


Figure 5. 2: Algorithm used for computing energy consumption of NC programs

After the software completes executing this algorithm, a window which displays results from the algorithm pops up. Figure 5. 3 shows this window. This window shows energy consumption of each NC program, as predicted by the software. The NC program which consumes the least amount of energy is highlighted in green. Results obtained from the software will be discussed in chapter 6.

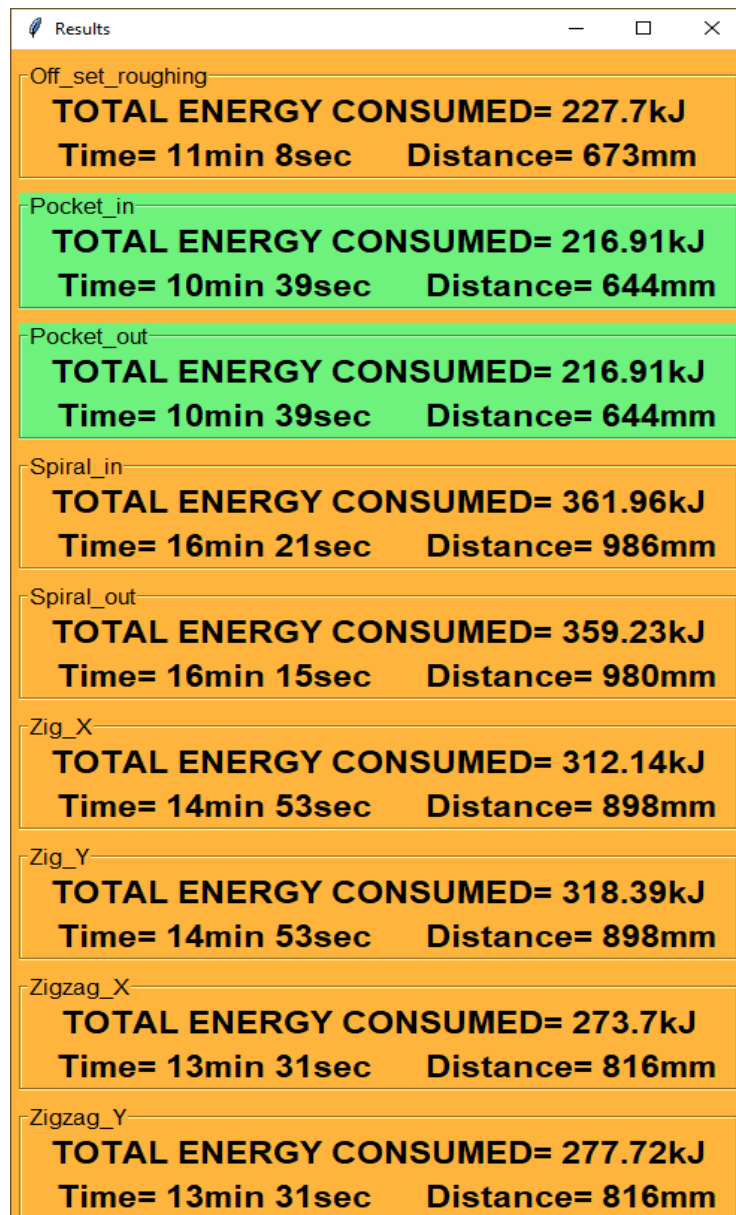


Figure 5. 3: A window showing energy consumption results from the software

Once the ‘Specifications’ button, shown in Figure 5. 1, is clicked, the GUI page shown in Figure 5. 4, will be displayed. Here, individual machine specifications and energy model constants are to be entered. These input parameters will be stored into a database once the ‘Submit’ button is clicked. The database used in this software is Sqlite3, which is built into python. This approach of using a database, eliminates some of the limitations which other software, discussed in chapter 2, possess. These software, are programmed to support only one CNC machine. The use of the database enables the CNC energy analyzer software to support multiple CNC machines. This is because specifications and constants for different CNC machine can be stored into the database, and be selected using drop down buttons.

CNC ENERGY ANALYZER SOFTWARE

Home Specifications

Name of machine

Name of material

Constants

P(fixed) = P(cool) = m =

P(tools magazine) = k =

	x	y	-Z	Z
a				
b				
c				
q				
u				
s				

Submit

Figure 5. 4: Specifications page of the GUI energy software

The CNC energy analyze GUI provides location for the reference point as shown in Figure 5. 1. This has been included to solve the problem of variation in percentage step-over of the cutting tool. Although CAM software aim to keep the percentage step-over during machining constant as set by the user, this is not always possible. It has been observed that during pocket milling, the tool cutting width is always at 100% of the cutting tool diameter for the initial cutting, which is equal to 100% percentage step-over. Figure 5. 5 shows power consumption of milling a rectangular pocket using pocket-in tool pathway strategy. Pocket-in tool pathway strategy is as shown in Figure 6. 1. As shown in Figure 5. 5, the power consumption is higher for the initial cutting, from point A to point B. This is because the percentage step-over between point A and point B is 100%, even though the percentage step-over has been set to 50%. From point C to point D, the power consumption is less, because the percentage overlap is maintained at 50% after the initial cut. The provision for reference point location shown in Figure 5. 1 solves this problem as the software is able to recognize the initialization point for the set percentage step-over during machining.

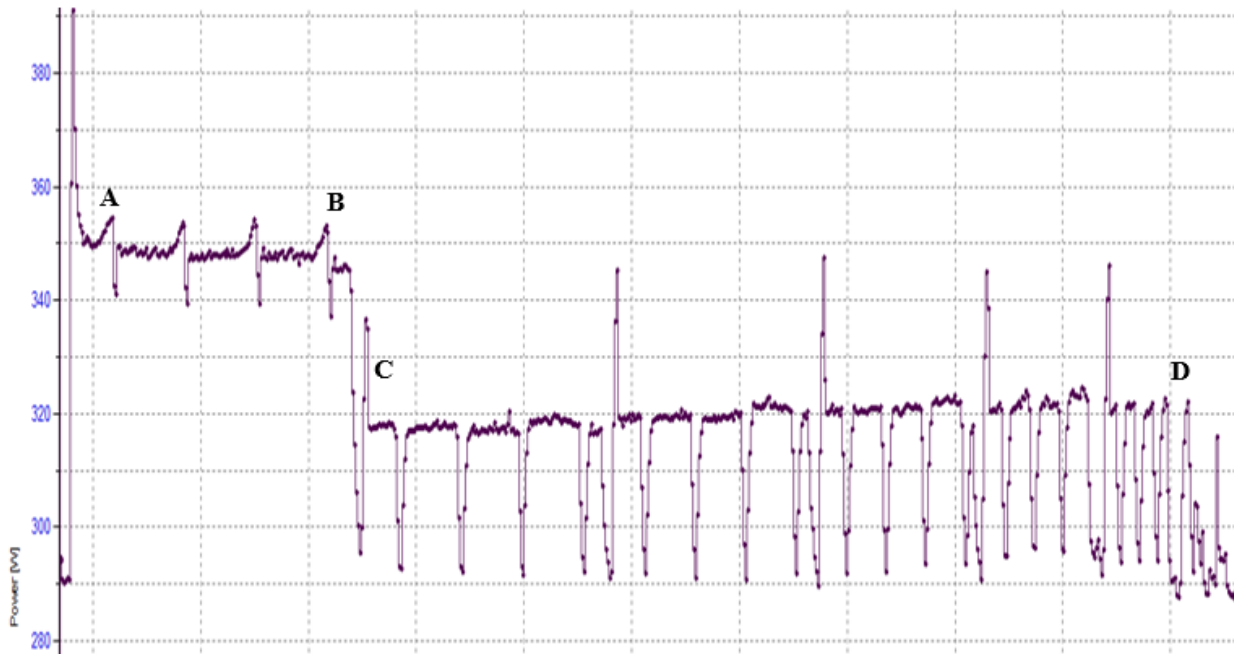


Figure 5. 5: Power consumption for milling a rectangular pocket using pocket-in tool pathway strategy.

5.3 Conclusion

The CNC energy analyzer software developed in this thesis has proved to take a step towards being readily applicable and more user friendly. The software has a database system which enables it to support various and numerous CNC machines. With the data base system, machinists can modify

energy model constants at any time during the life of the CNC machine. The next chapter uses results from the software to validate the software and analyze energy efficiency of different tool pathway strategies in CNC machining.

Chapter 6: RESULTS AND ANALYSIS

6.1 Introduction

In this chapter results from the CNC energy analyzer software are discussed. Experimental results obtained from the experimental set-up shown in chapter 3, are also presented. These experimental results are then compared to results obtained from the software, to investigate the validity of the software.

6.2 Validation of software and energy model

To validate the software, results displayed by the software are compared to results obtained experimentally. Experimental results were obtained using the experimental set-up presented in chapter 3. Validating the software, directly validate the CNC energy consumption model as the software utilizes the model to compute energy consumption for machining. The CNC energy consumption model referred to, in this chapter, has been presented in chapter 4.

To validate the CNC energy analyzer software and the CNC energy consumption model, nine different tool pathway strategies were used to machine rectangular and circular pockets on an aluminum 6061 block using a CNC machine. The energy consumption during machining, was then measure using the experimental set-up presented in chapter 3. The NC used for machining aluminum 6061 block was then fed to the software. The software then computes energy to be consumed based on the NC. The energy consumption measured experimentally is then compared to the energy consumption presented by the software to determine how accurate the predictions given by the software are. Schematic diagrams of the nine different tool pathways used in validation of the software and energy model are as shown in Figure 6. 1. These schematics are from Solidworks software (Dassault Systèmes, 2022). Solidworks software was used for generating NCs of the nine tool pathways strategies shown in Figure 6. 1 (Dassault Systèmes, 2022).

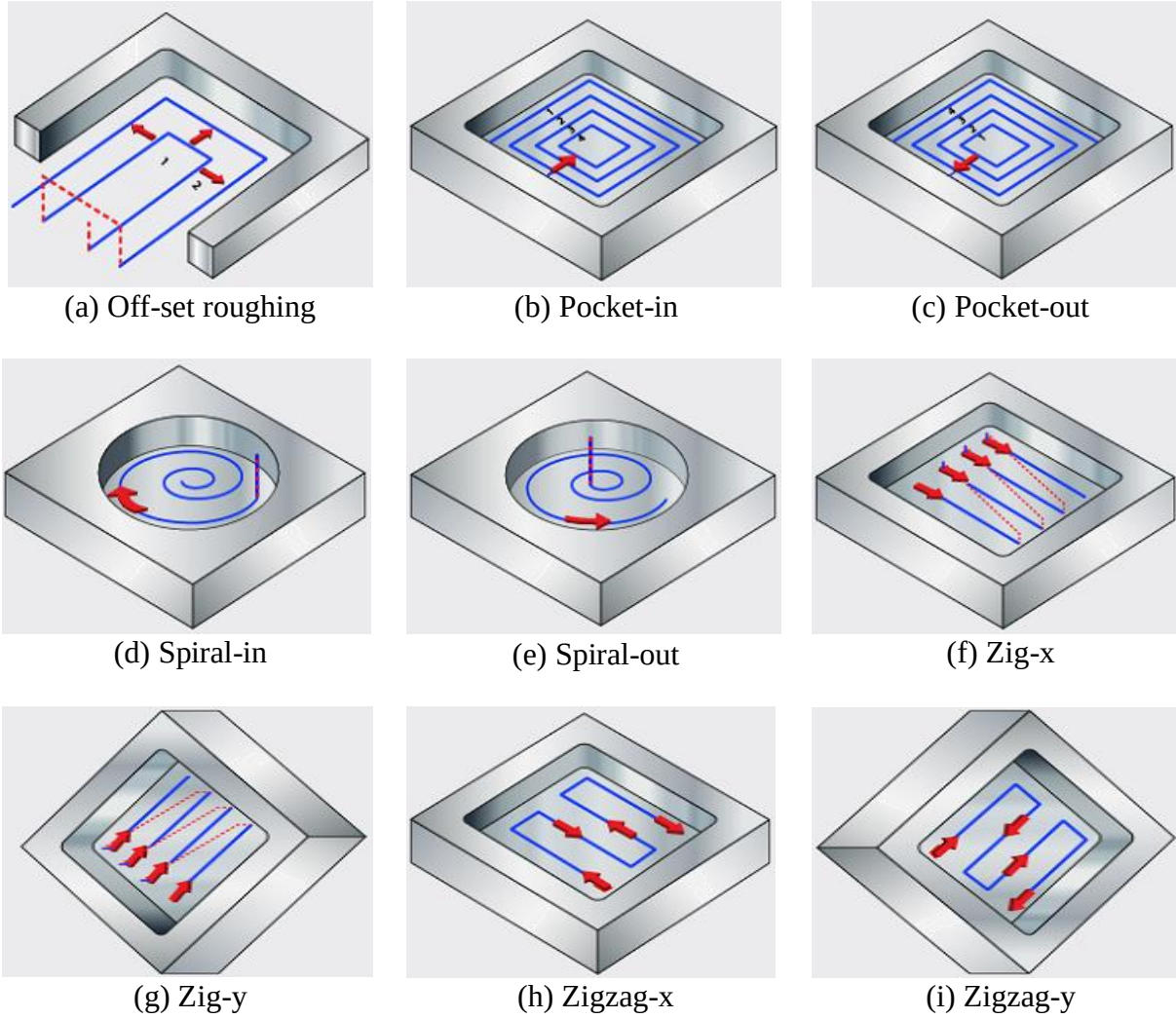


Figure 6. 1: Tool pathway strategies from Solidworks software (Dassault Systèmes, 2022).

For each tool pathway strategy, the cutting tool moves in trajectories shown in Figure 6. 1. The difference between zig-x and zig-y tool pathway strategies is that for zig-x, the cutting length shown in Figure 6. 1 (f) is along the x-axis, while for zig-y, the cutting length shown in Figure 6. 1 (g) is along the y-axis. In the same way, for zigzag-x, shown in Figure 6. 1 (h), the longer cutting lengths are along the x-axis, while for zigzag-y, shown in Figure 6. 1 (i), the longer cutting lengths are along the y-axis.

Using tool pathways shown in Figure 6. 1, rectangular pockets having dimensions of 46x46x2 mm were machined on aluminum 6160 block using a 6 mm end mill cutter. Images of aluminum blocks machined during the experiment are shown in Figure 6. 2. Tool marks showing the trajectory of the cutting tool during machining are visible on the aluminum blocks.

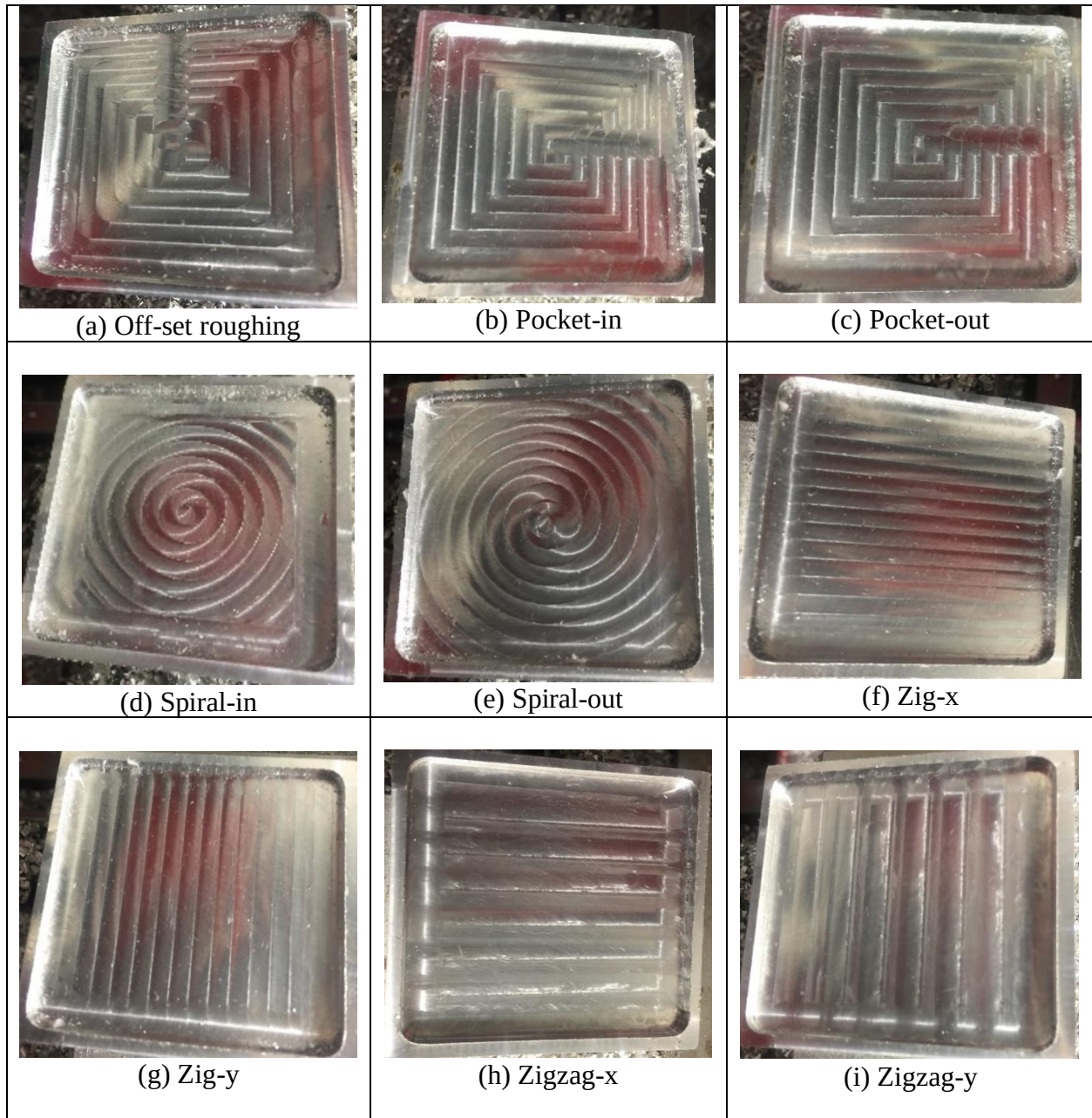
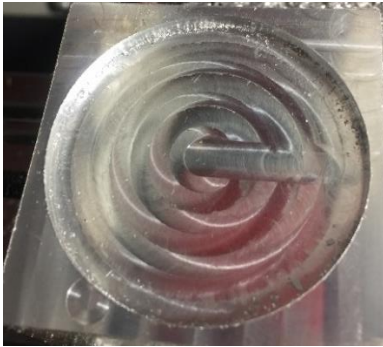
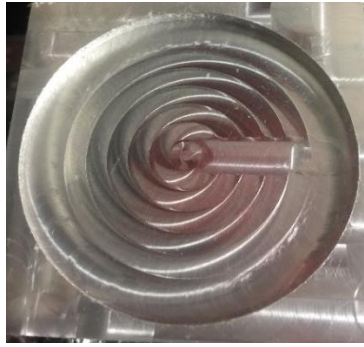


Figure 6. 2: Rectangular pockets machined on aluminum blocks using nine tool pathway strategies.

The nine tool pathway strategies shown in Figure 6. 1 were also used to machine circular pockets having diameter of 46mm and a depth of 2mm. Images of circular pockets machined on aluminum blocks are shown in Figure 6. 3. Tool marks showing the trajectory of the cutting tool during machining are visible on the aluminum blocks.



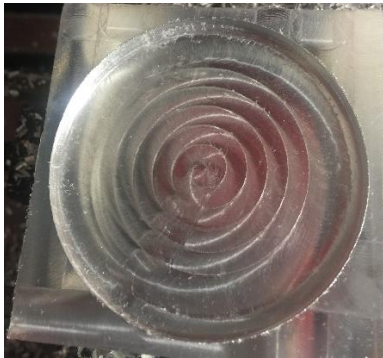
(a) Offset roughing



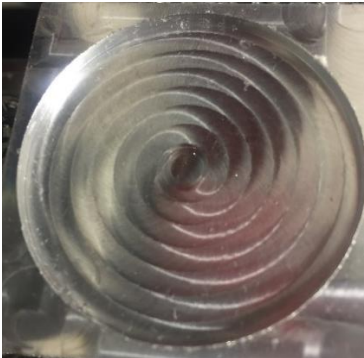
(b) Pocket-in



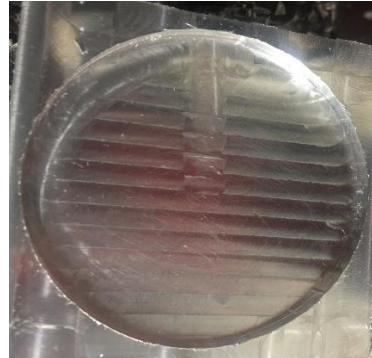
(c) Pocket-out



(d) Spiral-in



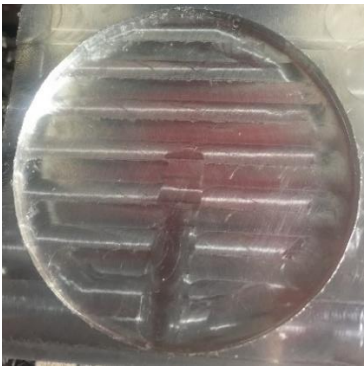
(e) Spiral-out



(f) Zig-x



(g) Zig-y



(h) Zigzag-x



(i) Zigzag-y

Figure 6. 3: Circular pockets machined on aluminum blocks using nine different tool pathway strategies.

The NC programs for the nine tool pathway strategies was fed to the CNC energy analyzer software. The software then computes energy to be consumed during machining based on NCs. Energy consumption predicted by the software and energy consumption measured from actual

machining of rectangular pockets are shown in Figure 6. 4. The machined rectangular pockets are as shown in Figure 6. 2.

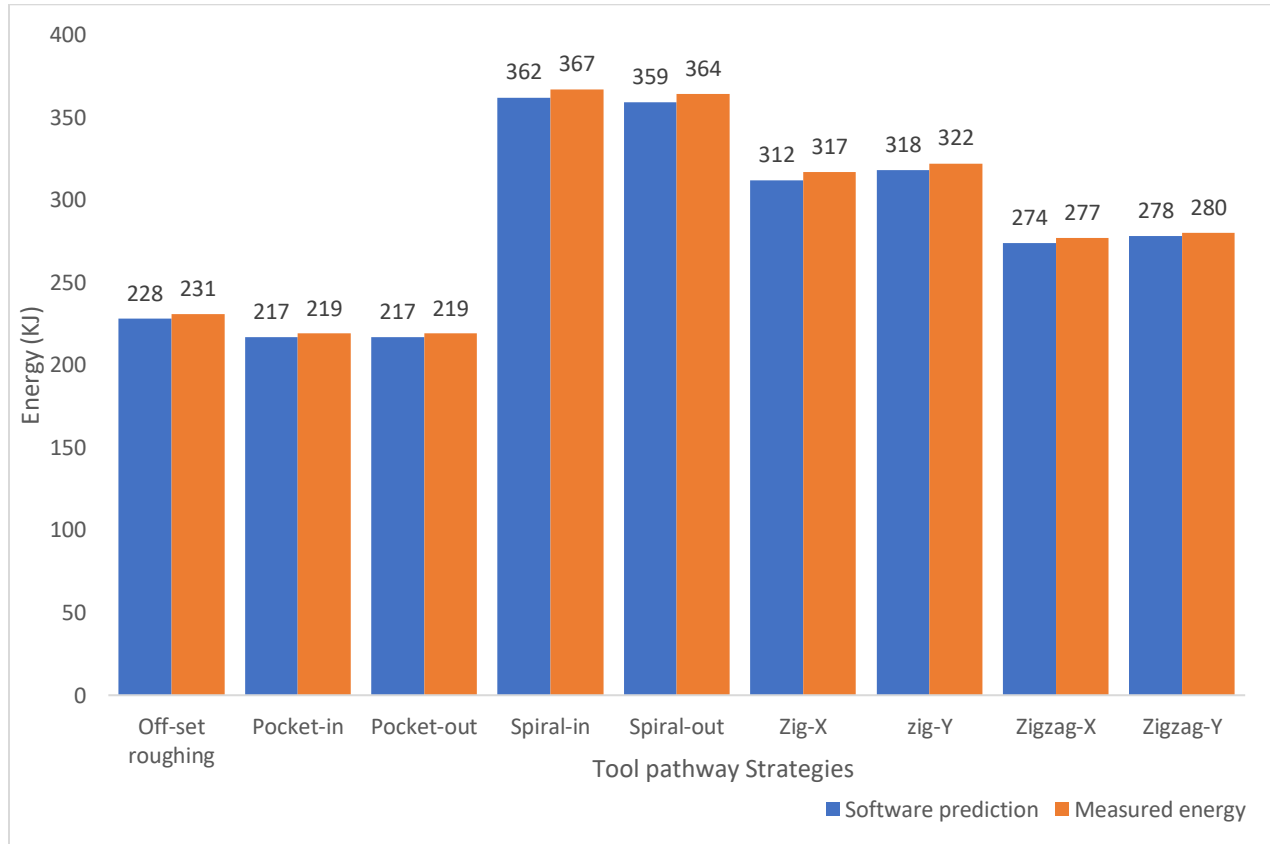


Figure 6. 4: Energy consumption predictions by software and measured energy consumption for machining rectangular pockets in a CNC machine.

Results shown in Figure 6. 4 show that there is significant variation in energy consumption across the nine tool pathway strategies in CNC machining. The results also show that the software predicted energy consumption in CNC machining with a high accuracy. Table 6. 1 shows percentage deviations of software results from the actual measured energy consumption. The greatest percentage deviation is -1.6%, for machining using the zig-x tool pathway strategy, as shown in Table 6. 1.

Table 6. 1: Percentage deviation of energy consumption predictions from measured results
(Rectangular pockets)

TOOL PATHWAY STRATEGY	% DEVIATION
Off-set roughing	-1.3
Pocket-in	-0.9
Pocket-out	-0.9
Spiral-in	-1.4
Spiral-out	-1.4
Zig-x	-1.6
zig-y	-1.2
Zigzag-x	-1.1
Zigzag-y	-0.7

The CNC energy analyzer software also predicts time duration for machining based on NCs. Time results for machining rectangular pockets are as shown in Figure 6. 5, from software predictions and from actual measurements.

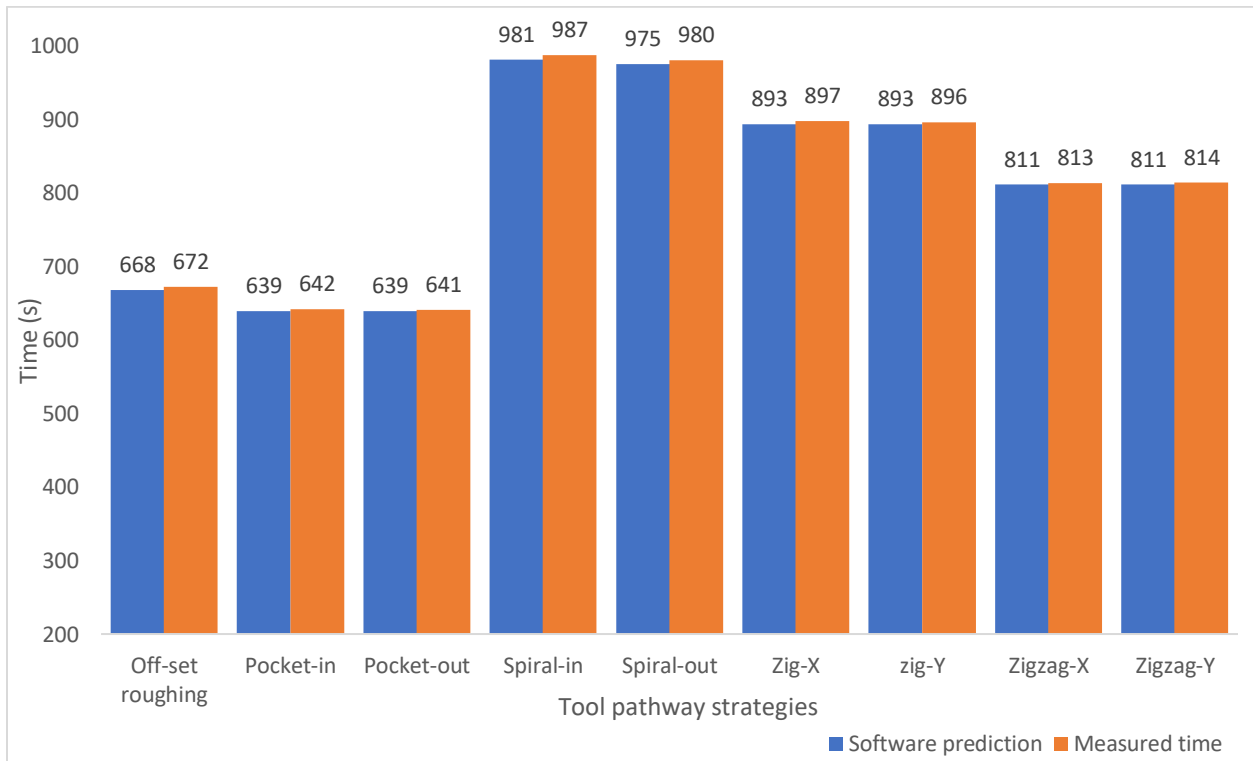


Figure 6. 5: Time duration predictions by software and measured time duration for machining rectangular pockets in CNC machining.

Time duration results for machining rectangular pockets shown in Figure 6. 5 show that there is significant variation in time duration across the nine tool pathway strategies, in CNC machining. The results also show that the software predicted time duration in CNC machining with a high accuracy. Table 6. 2 shows percentage deviations of software results from measured time duration for machining. The greatest percentage deviation is -0.6%, for machining using spiral-in and off-set roughing tool pathway strategies, as shown in Table 6. 2.

Table 6. 2: Percentage deviation of machining time duration predictions from measured results (Rectangular pockets)

TOOL PATHWAY STRATEGY	% DEVIATION
Off-set roughing	-0.6
Pocket-in	-0.5
Pocket-out	-0.3
Spiral-in	-0.6
Spiral-out	-0.5
Zig-x	-0.4
zig-y	-0.3
Zigzag-x	-0.2
Zigzag-y	-0.4

Energy consumption for machining circular pockets was also measured accordingly. The CNC energy analyzer software was fed with NCs for machining these circular pockets. The machined circular pockets are as shown in Figure 6. 3. The software then computed energy to be consumed during machining based on NCs. Energy consumption predicted by the software and energy consumption measured from machining of circular pockets are shown in Figure 6. 6.

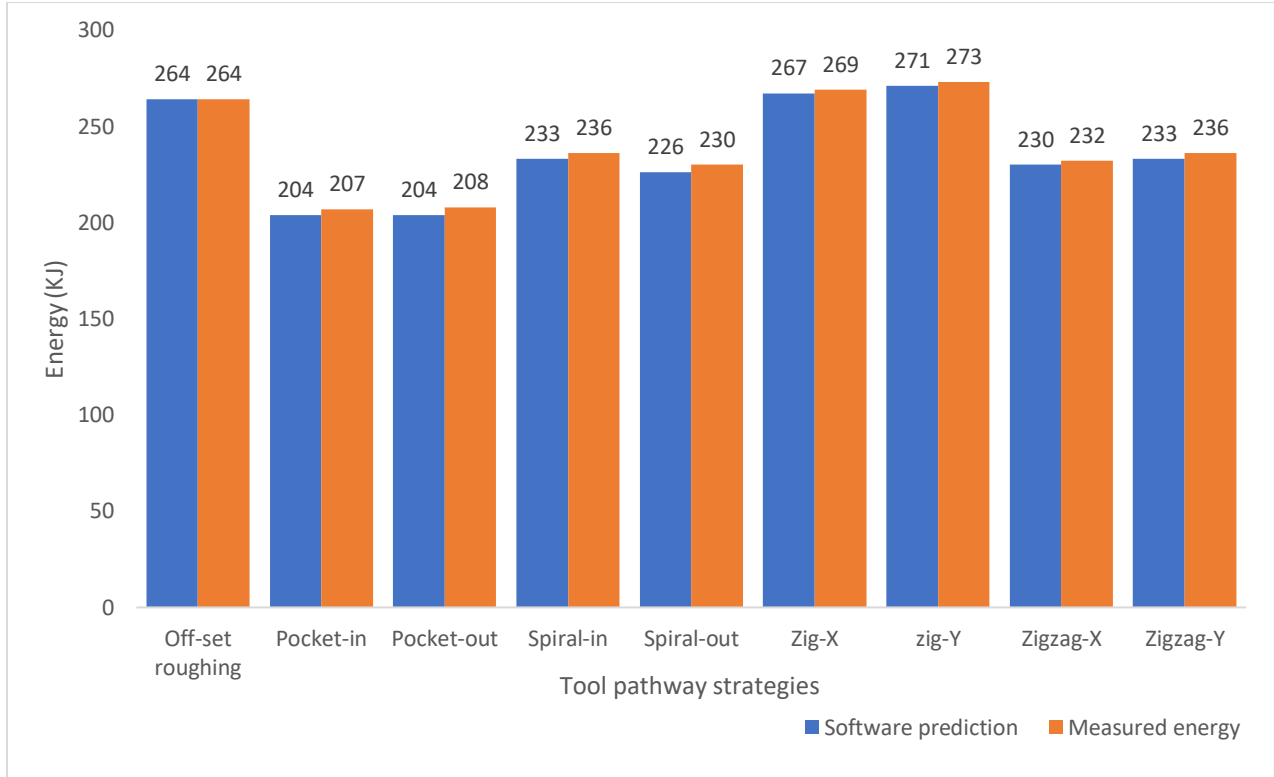


Figure 6. 6: Energy consumption predictions by software and measured energy consumption for machining circular pockets in a CNC machine.

The energy consumption results shown in Figure 6. 6 show that there is significant variation in energy consumption across the nine tool pathway strategies when machining circular pockets. The results also show that the software predicted the energy consumption in CNC machining with a high accuracy. Table 6. 3 shows energy consumption percentage deviations of software results from the actual measured results, for machining circular pockets. The greatest percentage deviation is -1.9%, for machining using the pocket-out pathway strategy, as shown in Table 6. 3.

Table 6. 3: Percentage deviation of energy consumption predictions from measured results
(Circular pockets)

TOOL PATHWAY STRATEGY	% DEVIATION
Off-set roughing	0.0
Pocket-in	-1.4
Pocket-out	-1.9
Spiral-in	-1.3
Spiral-out	-1.7
Zig-x	-0.7
zig-y	-0.7
Zigzag-x	-0.9
Zigzag-y	-1.3

The CNC energy analyzer software was also used to predict time duration for machining circular pockets based on NCs. The time duration for machining circular pockets was also measured during machining. The machining time duration results for machining circular pockets are shown in Figure 6. 7, from the software and from actual measurements.

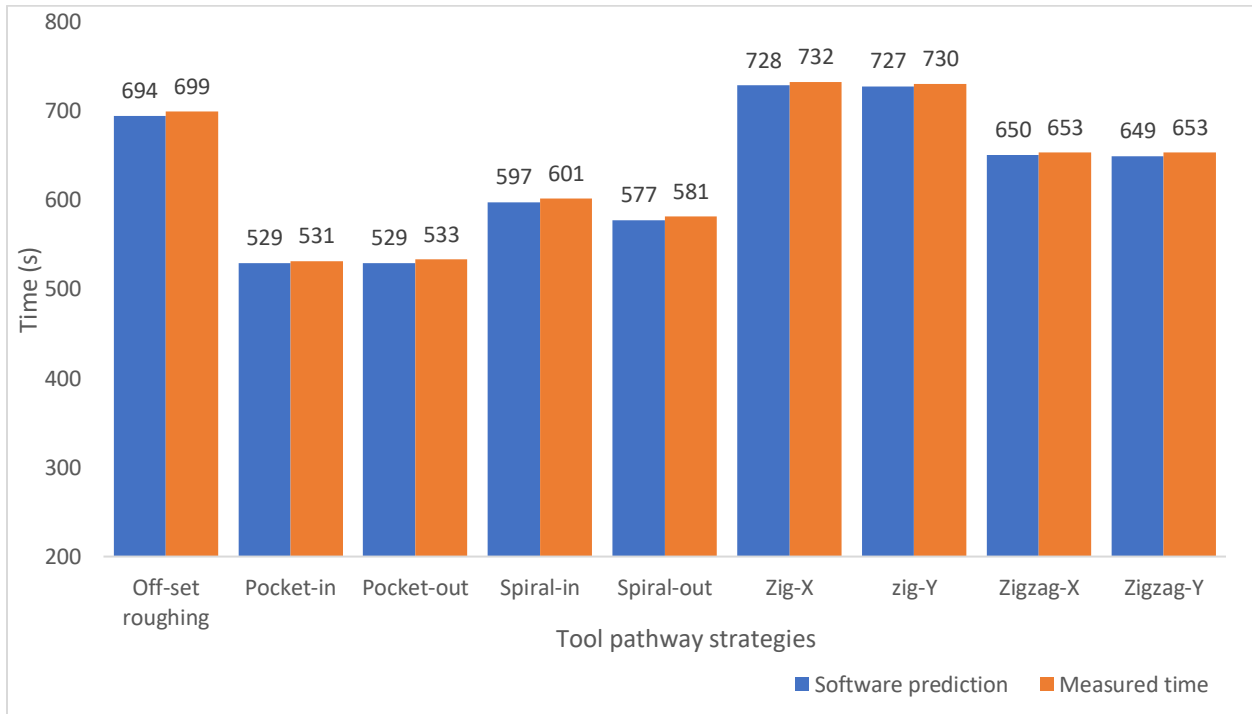


Figure 6. 7: Time duration predictions by software and measured time duration for machining circular pockets in CNC machining.

Time duration results for machining rectangular pockets shown in Figure 6. 7 also show that there is significant variation in time duration across the nine tool pathway strategies in machining of circular geometries. The results also show that the software predicted time duration for machining with a high accuracy. Table 6. 4 shows percentage deviations of software results from the actual measured results, for machining time duration. The greatest percentage deviation is -0.8%, for machining using pocket-out tool pathway strategy, as shown in Table 6. 4.

Table 6. 4: Percentage deviation of predicted machining time duration from measured time duration (Circular pockets)

TOOL PATHWAY STRATEGY	% DEVIATION
Off-set roughing	-0.7
Pocket-in	-0.4
Pocket-out	-0.8
Spiral-in	-0.7
Spiral-out	-0.7
Zig-x	-0.5
zig-y	-0.4
Zigzag-x	-0.5
Zigzag-y	-0.6

With the percentage deviations shown in Table 6. 1, Table 6. 2, Table 6. 3 and Table 6. 4, the CNC energy analyzer software has been considered to be valid enough for practical use. Percentage deviations shown in these tables are small enough to give accurate prediction and not produce anomalous results. Time predicted by the software was observed to be slightly lower than the measured time in all machining trials, as shown in Figure 6. 5 and Figure 6. 7. This may be due to the fact that actual acceleration of the feed axes may have been slightly lower than the acceleration value used in the software. The value of feed axes acceleration used in the software is 10 m/s^2 , as given in CNC machine manuals (I. Edem, 2016). This could have also been the reason why energy consumption predicted by the software is also slightly lower than the measured energy consumption in all trials, as energy consumption is a function of time among other variables.

The cutting operations performed for rectangular pockets are all made with linear interpolation code, G01. Therefore, using rectangular pocket does not validate circular interpolation codes, G02 and G03. However, Circular pockets are able to validate circular interpolation codes. This is because cutting operations in circular pockets uses both the linear interpolation codes and circular interpolation codes. It has been observed that the pocket-in and pocket-out tool pathway strategies are in particular well suited for validating circular interpolation codes. In these two tool pathway strategies, 92% of cutting operations is performed using circular interpolation. Linear interpolation codes are used just for repositioning the cutting tool for the next cutting operation. Appendix-A shows NC programs for machining a rectangular pocket and a circular pocket using the pocket-out tool pathway strategy, as was generated by Solidworks software (Dassault Systèmes, 2022). As discussed in chapter 2, previous studies only used rectangular geometries for validation of

energy models, therefore, circular interpolation codes were not validated. So, with all the validation experiments carried out in this research, it can be concluded that both cutting operations, linear interpolation and circular interpolation, were validated.

6.3 Energy consumption analysis based on tool pathway strategies

Having validated the CNC energy analyzer software, results from the software were used to analyze energy consumption in CNC machining with respect to tool pathway strategies. Tool pathway strategies considered are as shown in Figure 6. 1.

Figure 6. 8 shows energy consumption across the nine tool pathway strategies in relation to machining time duration. Results shown in Figure 6. 8 are for machining rectangular pockets shown in Figure 6. 2. Results show that tool pathway strategies that have longer time duration tend to consume more energy. These results further show that, for tool pathway strategies having the same time duration, orientation of the tool pathways should be considered in order to reduce energy consumption in CNC machining. As shown in Figure 6. 8, zig-y tool pathway strategy consumed more energy than zig-x tool pathway strategy, even though the two tool pathway strategies have equal time durations. Also, zigzag-y tool pathway strategy consumed more energy than zigzag-x tool pathway strategy. These two findings show that having the longer tool length oriented along the x-axis will reduce energy consumption in CNC machining.

Edem & Mativenga (2017) stated that the difference in power consumption along the x-axis and y-axis is due to the difference in weights of the two axes. Pavanaskar & McMains (2015) explained that the energy consumption differences are due to differences in feed axes construction, motor capacities, and bearing sizes. They further stated that, the Haas VF-0 machine has the x-axis mounted on top of the y-axis, as a result, when machining in the y-axis direction, the whole mass of the x-axis motors, bearings, and guides move as well.

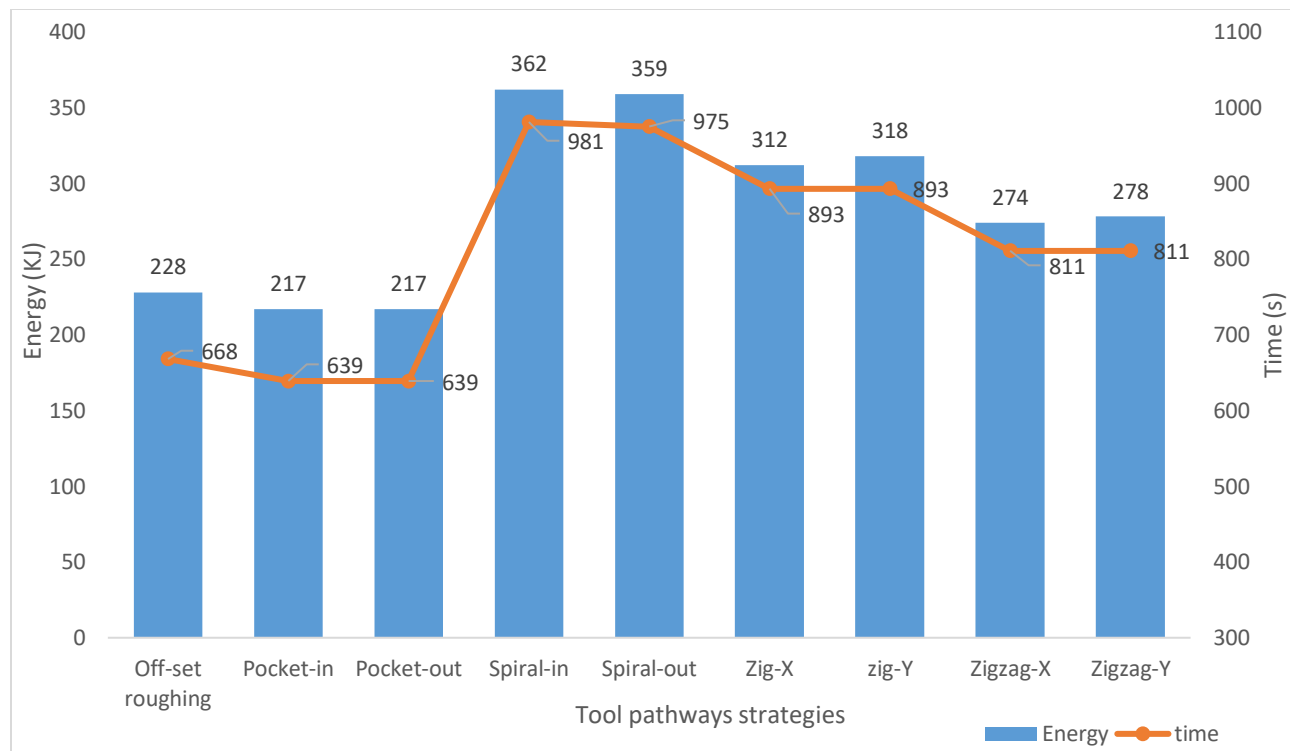


Figure 6. 8: Energy consumption in relation to time duration in CNC machining of rectangular pockets across the nine tool pathway strategies.

Figure 6. 9 shows energy consumption across the nine tool pathway strategies in relation to the distance travelled by the cutting tool on work piece. Results show that tool pathways that have longer distances travelled by the cutting tool tend to consume more energy. These results also show that, for tool pathways having equal cutting tool travel distance, orientation of the tool pathways should be considered in order to reduce energy consumption in CNC machining. As shown in Figure 6. 9, zig-y tool pathway strategy consumed more energy than zig-x tool pathway strategy, even though the two tool pathway strategies have equal travel distances. Also, zigzag-y tool pathway strategy consumed more energy than zigzag-x tool pathway strategy. These two findings further reveal that having the longer tool length oriented along the x-axis will reduce energy consumption in CNC machining.

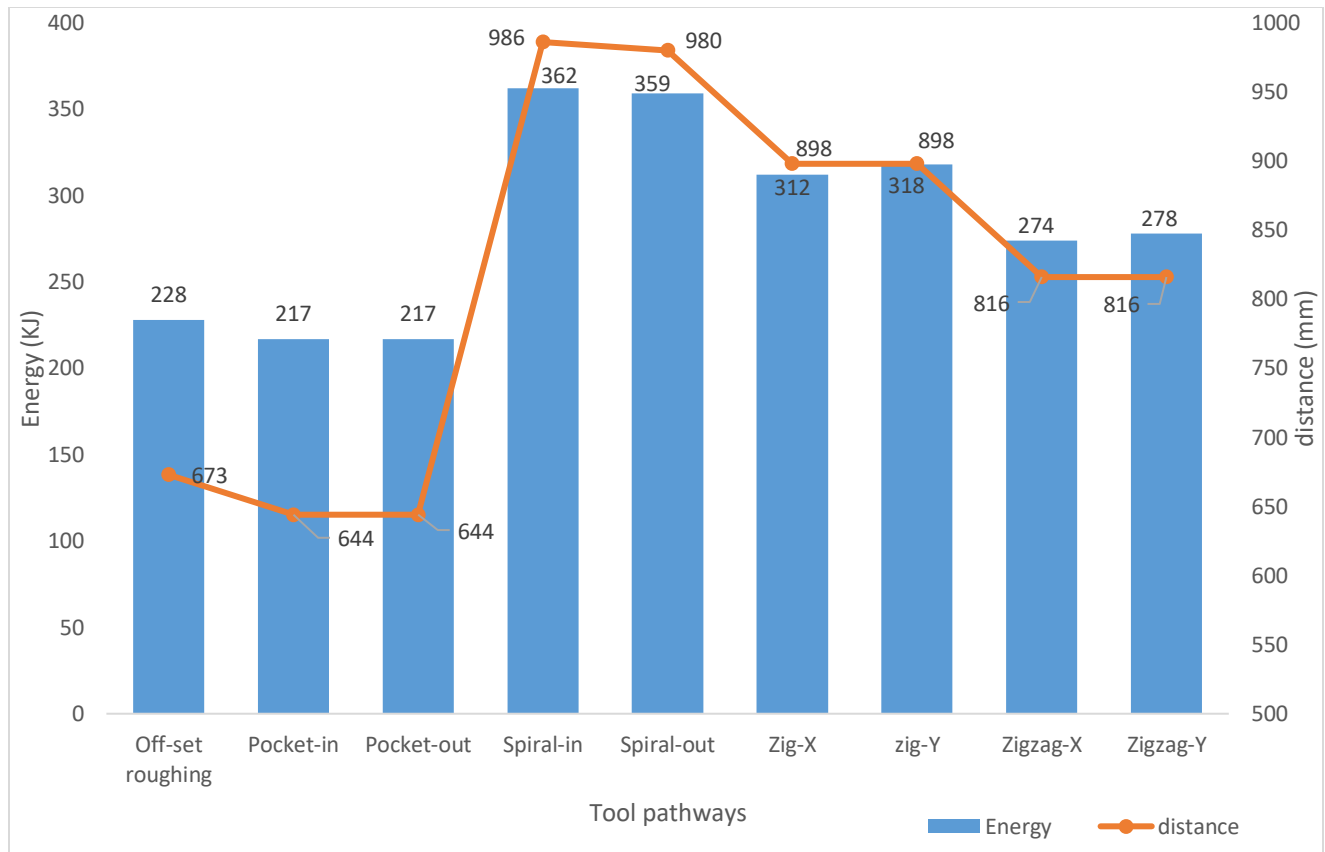


Figure 6. 9: Energy consumption in relation to cutting tool travel distance in CNC machining of rectangular pockets across the nine tool pathway strategies.

From Figure 6. 8 and Figure 6. 9, it can be observed that the spiral-in tool pathway consumed the most amount of energy for machining rectangular pocket. These results also show that spiral-in tool pathway strategy had the longest cutting tool travel distance and had the longest machining time duration. On the other hand, pocket-in and pocket-out tool pathway strategies consumed the least amount of energy, had the least cutting tool travel distance and had the least machining time duration. These results show that, by selecting the right tool pathway strategy, energy savings up to 67% could be achieved.

Results from the CNC energy analyzer software were also used to analyze energy consumption in CNC machining for machining circular geometries. Figure 6. 10 shows energy consumption across the nine tool pathway strategies in relation to the machining time duration. Results shown in Figure 6. 10 are for machining circular pockets, shown in Figure 6. 3. These results also show that tool pathway strategies that have longer time duration consume more energy. These results further show that, for tool pathways having the same time duration, orientation of the tool pathways should be considered in order to reduce energy consumption in CNC machining. As shown in Figure 6. 10, zig-y tool pathway strategy consumed more energy than zig-x tool pathway strategy. Also,

zigzag-y tool pathway strategy consumed more energy than zigzag-x tool pathway strategy. These two findings also show that having the longer tool length oriented along the x-axis will reduce energy consumption in CNC machining.

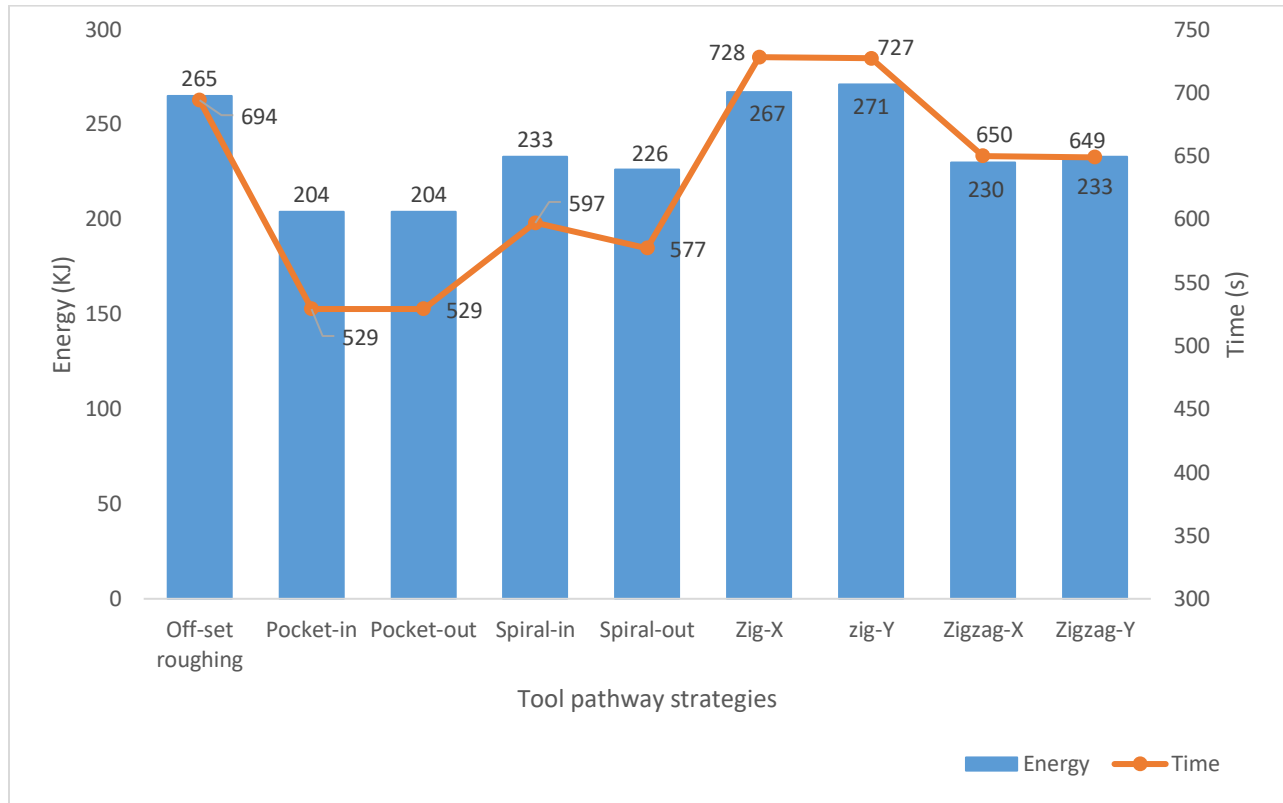


Figure 6. 10: Energy consumption in relation to time duration in CNC machining of circular pockets across the nine tool pathway strategies.

Figure 6. 11 shows energy consumption across the nine tool pathway strategies in relation to the distance travelled by the cutting tool on work piece. Results show that tool pathways that have longer travel distances consume more energy. These results further show that, for tool pathway strategies having equal travel distances, orientation of tool pathways should be considered in order to reduce energy consumption in CNC machining. As shown in Figure 6. 11, zig-y tool pathway strategy consumed more energy than zig-x tool pathway strategy. Also, zigzag-y tool pathway strategy consumed more energy than zigzag-x tool pathway strategy. These two findings further reveal that having the longer tool length oriented along the x-axis will reduce energy consumption in CNC machining.

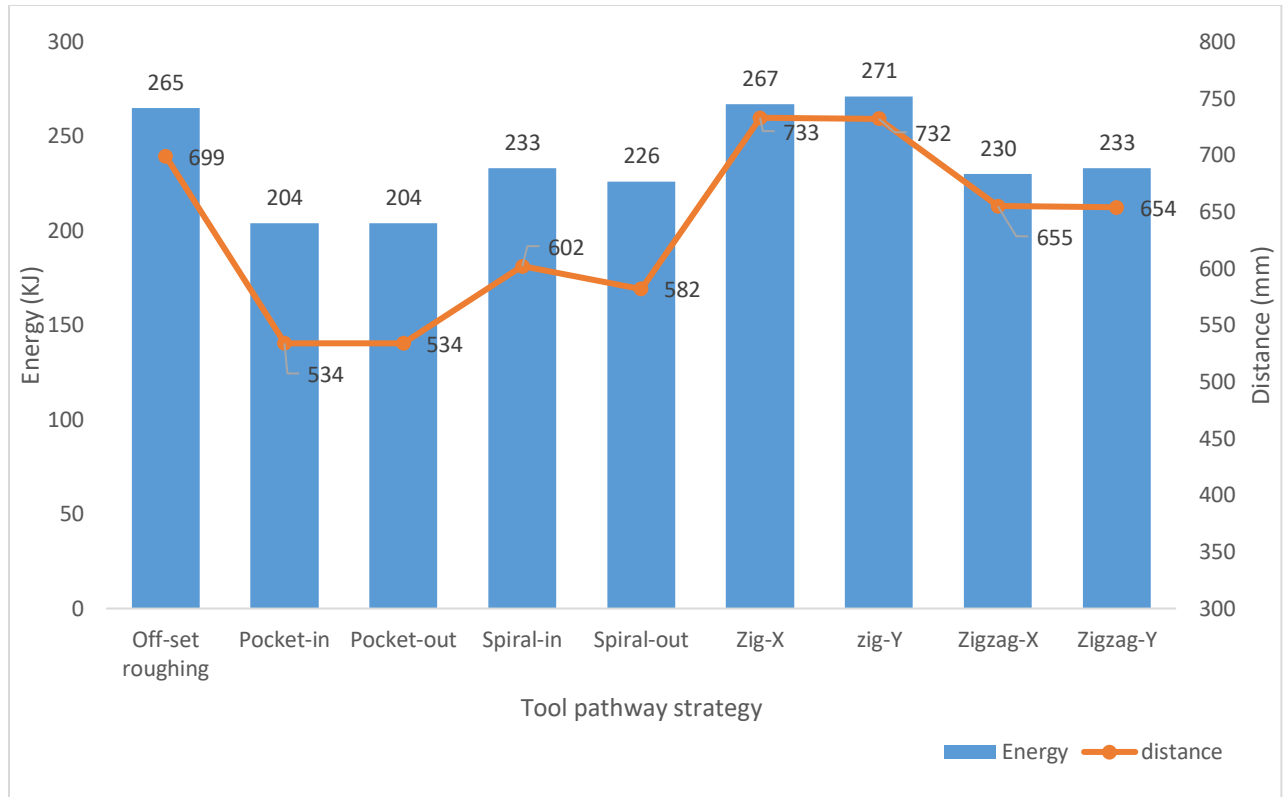


Figure 6. 11: Energy consumption in relation to cutting tool travel distance in CNC machining of circular pockets across the nine tool pathway strategies.

From Figure 6. 10 and Figure 6. 11, it can be observed that the zig-y tool pathway strategy consumed the most amount of energy, had the longest cutting tool travel distance and had the longest machining time duration, when machining circular pockets. On the other hand, pocket-in tool pathway strategy and pocket-out tool pathway strategy consumed the least amount of energy, had the least cutting tool travel distance and had the least machining time duration. These results show that, by selecting the right tool pathway strategy, energy savings up to 33% can be achieved, in machining circular pockets.

Results from Figure 6. 8, Figure 6. 9, Figure 6. 10 and Figure 6. 11 show that energy consumption rate of the different tool pathways depends on the geometry being machined. For circular pockets, the zig-y tool pathway consumes the most amount of energy, while for rectangular pockets, spiral-in tool pathway consumes the most amount of energy. Off-set tool pathway strategy consumes relatively small amount of energy in rectangular pockets than in circular pockets. Energy savings for rectangular pockets are up to 67%, while in circular pockets, energy savings are up to 33%. However, for both geometries, it has been observed that pocket-in and pocket out tool pathway strategies are the most energy efficient tool pathways.

6.4 Conclusion

In this chapter the energy analyzer software and the energy consumption model were validated. The software was able to predict energy consumption in CNC machining to a high degree. Results presented in this chapter also revealed that by selection of the most energy efficient tool pathway strategy, considerable amounts of energy savings could be achieved.

Chapter 7: CONCLUSION

7.1 Conclusion

To deal with the high energy consumption faced by manufacturing industries, this thesis proposes energy saving strategies for CNC machining. This thesis has introduced a novel energy consumption model for three axis CNC milling machines. The model presented in this thesis computes energy consumption of any three axis CNC machine based on any given numeric code. This energy model supports all machining operations which may be performed on a three axis CNC machine. The model also considers weight of the work piece in a more simplified approach. An energy analyzer software was developed to compute energy consumption in CNC machining, based on NC codes. This energy analyzer software, utilizes the energy model developed in this thesis to compute energy to be consumed by CNC machines. By conducting some machining trials, the energy model and the software were validated. The greatest percentage deviation of the software energy predictions from the measured energy consumption was -1.9%.

The energy software developed was shown to be useful in the selection of energy efficient tool pathways for CNC machining. Nine tool pathway strategies were studied in this thesis using the energy analyzer software developed. The energy consumption of the nine tool pathway strategies was examined on two geometries, the rectangular pocket and the circular pocket. Results from the software revealed the pocket-in and the pocket-out tool pathways were the most energy efficient tool pathway strategies for both the rectangular pocket and the circular pocket. Spiral-in tool pathway strategy had the highest energy demand in rectangular pockets while zig-y tool pathway strategy had the highest energy demand in circular pockets. Results from the software revealed that, energy efficiency of different tool pathway strategies vary with respect to the geometry being machined. With the significant variation of energy consumption across the nine tool pathway strategies, the energy savings were up to 67 % for rectangular pockets and up to 33% for circular pockets. Using a software to select energy efficient tool pathways for machining is a cheaper and faster process than doing machining trials to select the most energy efficient tool pathways.

The CNC energy consumption model has constants which are to be determined experimentally by conducting machining trials. The energy analyzer software developed in this thesis allows users to store the CNC energy model constants. These constants are unique to each CNC machine. To aid in making the software easy to use, CNC machine manufacturers could consider providing these constants to end users. The end user will then be able to use the software without having to conduct machining trials to determine machine constants. Incorporating the energy analyzer software into CAM software packages will further aid in making the energy analyzer software to be user friendly and be accessible to a large audience of manufacturers.

7.2 Future work

With regard to tools and information provided by this thesis, the following research areas are proposed for future work:

- Development of new tool pathway strategies with the focus being on improving energy efficiency in CNC machining. These newly developed tool pathway strategies could then be analyzed using the energy analyzer software developed in this thesis.
- Study of the effects of tool wear on energy consumption in CNC machining. This study will show how CNC machines consume energy as the cutting tool wears out. With this study, recommendations on when it is best to change the cutting tool in order to improve machining energy efficiency may be developed.
- Development of a maintenance management system for CNC machines, which focuses on improving energy efficiency in CNC machining.

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APPENDICES

Appendix A: NCs for pocket-out tool pathway strategy

NC for Pocket-out tool pathway strategy (Circular pocket)

O0001;
N1 G21;
N3 G91 G28 X0 Y0 Z0;
N4 T02 M06;
N5 S2500 M03;
N7 G90 G54 G00 X25. Y25.;
N8 G43 Z2.5 H02 M08;
N9 G01 Z-2. F60.;
N10 G17 X27.;
N11 G03 I-2. J0;
N12 G01 X30.;
N13 G03 I-5. J0;
N14 G01 X33.;
N15 G03 I-8. J0;
N16 G01 X36.;
N17 G03 I-11. J0;
N18 G01 X39.;
N19 G03 I-14. J0;
N20 G01 X42.;
N21 G03 I-17. J0;
N22 G01 X45.;
N23 G03 I-20. J0;
N24 I-20. J0;
N25 G01 X25.;
N26 G00 Z2.5;
N27 Z25. M09;
N28 G91 G28 Z0;
N29 G28 X0 Y0;
N30 M30;

NC for Pocket-out tool pathway strategy (Rectangular pocket)

O0001;
N1 G21;
N3 G91 G28 X0 Y0 Z0;
N4 T02 M06;
N5 S2500 M03;
N7 G90 G54 G00 X23. Y27.;
N8 G43 Z2.5 H02 M08;
N9 G01 Z-2. F60.;
N10 G17 Y23.;
N11 X27.;
N12 Y27.;
N13 X23.;
N14 Y30.;
N15 X20.;
N16 Y20.;
N17 X30.;
N18 Y30.;
N19 X23.;
N20 Y33.;
N21 X17.;
N22 Y17.;
N23 X33.;
N24 Y33.;
N25 X23.;
N26 Y36.;
N27 X14.;
N28 Y14.;
N29 X36.;
N30 Y36.;
N31 X23.;
N32 Y39.;
N33 X11.;
N34 Y11.;
N35 X39.;
N36 Y39.;
N37 X23.;
N38 Y42.;
N39 X8.;
N40 Y8.;

N41 X42.;
N42 Y42.;
N43 X23.;
N44 Y45.;
N45 X5.;
N46 Y5.;
N47 X45.;
N48 Y45.;
N49 X23.;
N50 X5.;
N51 Y5.;
N52 X45.;
N53 Y45.;
N54 X23;
N55 G00 Z2.5;
N56 Z25. M09;
N57 G91 G28 Z0;
N58 G28 X0 Y0;
N59 M30;