UC Berkeley
UC Berkeley Electronic Theses and Dissertations

Title
Environmental impact estimation of mold making process

Permalink
https://escholarship.org/uc/item/3jq403dn

Author
Kong, Daeyoung

Publication Date
2013

Peer reviewed|Thesis/dissertation

eScholarship.org Powered by the California Digital Library
University of California

Environmental impact estimation of mold making process

by

Daeyoung Kong

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Engineering - Mechanical Engineering

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor David Dornfeld, Chair

Professor Paul Wright

Professor Sara Beckman

Fall 2013

Environmental impact estimation of mold making process

©2013

by

Daeyoung Kong

Abstract

Environmental impact estimation of mold making process

by

Daeyoung Kong

Doctor of Philosophy in Engineering - Mechanical Engineering

University of California, Berkeley

Professor David Dornfeld, Chair

Increasing concern of environmental sustainability regarding depletion of natural resources and resulting negative environmental impact has triggered various movements to address these issues. Various regulations about product life cycle have been made and applied to industries. As a result, how to evaluate the environmental impact and how to improve current technologies has become an important issue to product developers. Molds and dies are very generally used manufacturing tools and indispensible parts to the production of many products. However, evaluating environmental impact in mold and die manufacturing is not well understood and not much accepted yet.

The objective of this thesis is to provide an effective and straightforward way of environmental analysis for mold and die manufacturing practice. For this, current limitations of existing tools were identified. While conventional life cycle assessment tools provide a lot of life cycle inventories, reliable data is not sufficient for the mold and die manufacturer. Even with comprehensive data input, current life cycle assessment (LCA) tools only provide another comprehensive result which is not directly applicable to problem solving. These issues are critical especially to the mold and die manufacturer with limited resource and time.

This thesis addresses the issues based on understanding the needs of mold and die manufacturers. Computer Aided Manufacturing (CAM) is the most frequently used software tool and includes most manufacturing information including the process definition and sometimes geometric modeling. Another important usage of CAM software tools is problem identification by process simulation. Under the virtual environment, possible problems are detected and solved. Environmental impact can be handled in the same manner. To manufacture molds and dies with minimizing the associated environmental impact, possible environmental impact sources must be minimized before execution in the virtual environment.

Molds and dies are manufacturing-intensive products and most of their environmental impact is generated by energy consumption during the machining processes. Milling and Electric

Discharge Machining (EDM) operations were selected as the most influential mold and die manufacturing processes. Process variability was found to be the key issue which must be addressed for reliable analysis. Acceleration and deceleration in the milling process and the dielectric contamination and resultant decrease of material removal rate (MRR) in the EDM process were identified as main factors for the variability. Energy consumption of these two processes were analyzed and modeled including the variability. Experiments were carried out to validate and improve this model. Finally, this model is implemented as simulation software tools on the basis of CAM software (Esprit CAM^{TM}).

The CAM-based tool developed in this study can be more easily used in the mold and die manufacturing practice. Considering the variety of molds and dies and their application, this tool would be just a small step along the way to environmentally benign mold and die manufacturing. However, with further research, the tool developed in this thesis will result in an effective way to address environmentally benign mold and die manufacturing.

To My Family

Table of Contents

Table of Contents. ii

List of Figures vi

List of Tables. ix

Acknowledgement x

Curriculum Vitae and Publications. xi

Chapter 1 Introduction 1
1.1 Environmental sustainability 1
1.1.1 Energy & resource concerns 1
1.1.2 Influence of manufacturing sector 3
1.2 Metal fabrication and the environmental impact 5
1.2.1 Plant based manufacturing sector 5
1.2.2 Fabricated metal manufacturing sector 5
1.2.3 Machine tool energy consumption 6
1.3 Objective of this dissertation 7
1.4 Contribution of this research 7
1.5 Outline of dissertation 8
Chapter 2 Mold and Die Manufacturing 9
2.1 Introduction to molds and dies 9
2.2 Molds and dies 9
2.3 Influence of molds and dies in the product development 11
2.4 Environmental impact of mold and die 13
2.5 Conclusion 15
Chapter 3 Information System and Mold and die manufacturing 16
3.1 Introduction 16
3.2 Information system and energy consumption in mold making 17

3.3 Life cycle assessment (LCA) tools 18
3.4 CAD-based LCA tools 19
3.5 LCA tools for mold and die manufacturing 20
3.6 Conclusion 21
Chapter 4 Environmental Impact of CNC Milling 23
4.1 Introduction 23
4.2 Environmental impact of the manufacturing process 23
4.3 Breakdown of Energy Consumption of CNC Milling Machines 25
4.4 Current methods 26
4.4.1 Power demand information for CNC milling components 26
4.4.2 Specific energy of CNC milling process 28
4.4.3 Limitation of current methods 30
4.5 Cutting Power of Milling Process 31
4.6 Acceleration and Deceleration 34
4.7 Structural Configuration of a Machine Tool and Direction of Axes Movement 39
4.8 Tare energy and cycle time prediction 41
4.9 Impact of Geographical Region on the Green House Gas Emission 42
4.10 Experimental Validation 44
4.10.1 Rectangular pocket tool path 46
4.10.2 Curved profiles 47
4.10.3 Influence of the segment length 49
4.11 Milling process and software simulation 49
4.12 Modeling 50
4.13 Implementation 51
4.13.1 Web-based Software Implementation 51
4.13.2 API-based Software Implementation 52
4.14 Test Cases 53
4.14.1 Rectangular pocket milling with different tool path patterns 53
4.14.2 Various surface shapes with different tool path patterns 55
4.15 Conclusion 57
Chapter 5 Environmental impact of Electric discharge machining 59

5.1 Introduction 59
5.2 Basic theory of EDM 60
5.2.1 Die sinking EDM and wire-EDM 61
5.2.2 EDM components 62
5.3 Process parameters in EDM 63
5.3.1 Single discharge 63
5.3.2 Discharge cycle 66
5.3.3 Gap control and flushing 69
5.3.4 Electrode material 71
5.4 Cycle time variance consideration 71
5.4.1 Time delay during pulse on time 71
5.4.2 Inconsistent MRR 72
5.5 Environmental impact of EDM 74
5.5.1 Energy consumption for material removal in EDM 75
5.5.2 Peripheral devices 76
5.5.3 Waste of material 76
5.5.4 Energy consumption of EDM 77
5.6 Machine data acquisition 78
5.6.1 Experiment setup and restrictions 78
5.6.2 Experiment results and consideration 79
5.7 Modeling 81
5.8 Implementation 81
5.9 Test case and analysis 82
5.10 Conclusion 83
Chapter 6 Environmental Impact of Mold Making 85
6.1 Introduction 85
6.2 Software simulation in mold and die manufacturing 86
6.3 CAM-based environmental impact estimation 86
6.4 Test Case and analysis 87
6.5 Process planning 89
6.6 Conclusion 90

Chapter 7 Summary and Conclusions 91
7.1 CAM-based process analysis of molds and dies making 91
7.2 Future works 91
7.2.1 Collaborative mold and die manufacturing 92
7.2.2 The leveraging impact of molds and dies 93
Bibliography 95
Appendix A Estimation Software Tool 104
A.1 Esprit API 104
A.2 Graphic User Interface 105
A.2.1 Operation Analysis Dialog 105
A.2.2 Milling Operation Dialog 107
A.2.3 EDM Operation Dialog 108

List of Figures

Figure 1.1. Crude Oil Price Change [1] 2
Figure 1.2. U.S. Electricity Production Costs (C/kWh) [2] 2
Figure 1.3. World atmospheric concentration of CO2 and average global temperature change [3] 3
Figure 1.4. (a) Total final energy consumption and (b) total direct and indirect CO2 emissions [7] 4
Figure 1.5. Primary energy use and emissions in U.S. Manufacturing sectors [8] 4
Figure 1.6. LCA results of machine tool use phase [10] 6
Figure 2.1. (a) Molds for cell-phone covers and (b) dies for automobile cover sheet metal body components 10
Figure 2.2. Basic mold base structure and injection molding mechanism 11
Figure 2.3. (a) Global mold and die production values and [28] (b) mold and die market needs in different countries [29] 12
Figure 2.4. Process parameters of mold & die manufacturing process 13
Figure 2.5. (a) Life cycle cost of progressive die [33], (b) automotive part by injection molding [34] 14
Figure 2.6. Time distribution in mold making [36] 14
Figure 3.1. Various software tools in product development 16
Figure 3.2. (a) Gabi4 LCA Tool [PE International], (b) Registration year of life cycle inventory data in NREL database 18
Figure 3.3. Environmental impact estimation based on two main processes 21
Figure 4.1. Resource flow for manufacturing processes [13] 24
Figure 4.2. Machining energy breakdown for a 1998 Bridgeport milling machine [14] 25
Figure 4.3. Variation of energy consumption over a range of different feed speeds [46] 27
Figure 4.4. Specific energy as a function of MRR for Mori Seiki NVD 1500 [50] 29
Figure 4.5. Specific electricity requirements for various manufacturing processes [51] 30
Figure 4.6. Visualized (a) tool swept volume and (b) machined workpiece in milling operations [56] 31
Figure 4.7. Geometric schematic of the vertical milling operation (climb milling) (a) isometric and (b) top view 32
Figure 4.8. Impact of surface geometric complexity and programmed feed rate on the actual cycle time during HSM [61] 35
Figure 4.9. Acceleration and deceleration of machine tool axes to reach a specified feed rate 36
Figure 4.10. (a) Acceleration and deceleration of machine tool axes with small direction change, (b) position discrepancy in tool trajectory 37
Figure 4.11. Temporal deviation according to tool path segment length 39
Figure 4.12. Different power demand of jogging the Mori Seiki NVD 1500 milling machine 40
Figure 4.13. Maximum feed rate and direction of cutting tool movement. 41
Figure 4.14. Power consumption distribution of Mori Seiki NVD1500 [66] 41
Figure 4.15. Energy mix in the USA from U.S. EIA 08 [7] 44
Figure 4.16. Energy mix of several countries for electricity generation [74] 44

Figure 4.17. Power meter (CW240) connection to NVD 1500 45
Figure 4.18. Rectangular pocket and curved profile tool paths 45
Figure 4.19. Power profile and machining for rectangular pocket milling 46
Figure 4.20. Power profile with different load conditions 47
Figure 4.21. Power profile of curves profile milling with 800mm/min feed rate 48
Figure 4.22. Power profile of curves profile milling with 1500mm/min feed rate 48
Figure 4.23. Discrepancy rate of actual cycle time to ideal time in (a) a rectangular pocket tool paths and in (b) a curved profile. 49
Figure 4.24. Process flow for tool path planning incorporating a sustainability concern 50
Figure 4.25. Architecture of the simulation software 51
Figure 4.26. Web-based simulation environment 52
Figure 4.27. API-based simulation environment 53
Figure 4.28. Processing time and energy consumption of various tool-paths 54
Figure 4.29. GHG emissions resulted from executing a sample tool path in five arbitrarily chosen states (Figure 4.29 (a) shows all the GHG emissions and Figure 4.29 (b) shows the GHGs except carbon dioxide.) 55
Figure 4.30. Tool path influence on the cycle time variation 56
Figure 4.31. Green house gas emission as a result of electricity consumption for machining a pocket shown in the left in Indiana 56
Figure 5.1. Die sinking EDM usage by applications [35] 59
Figure 5.2. Material removal by electric discharge 61
Figure 5.3. (a) Die sinking EDM and (b) 2 axis wire-EDM 62
Figure 5.4. EDM operation parameters 63
Figure 5.5. MRR versus current size for various duty cycles [86] 64
Figure 5.6. MRR versus discharge voltage for various electric resistances [87] 65
Figure 5.7. MRR and pulse duration time for different discharge currents [93] 65
Figure 5.8. Discharge cycles of pulses in EDM 67
Figure 5.9. Three types of flushing in EDM 69
Figure 5.10. Electrode jump up/down time in jet flushing 70
Figure 5.11. Servo feed control [97] 72
Figure 5.12. Machining depth and MRR change [99] 72
Figure 5.13. (a) Jump height and machining depth relation in EDM and (b) schematics of flushing [100] 73
Figure 5.14. EDM ecological block scheme [82] 74
Figure 5.15. EDM power demands [80] 76
Figure 5.16. EDM experimental setup and data acquisition 78
Figure 5.17. Material removal depth with the current sizes 79
Figure 5.18. MRR across different current sizes 80
Figure 5.19. (a) Machining depth with time and (b) corresponding duty factor 80
Figure 5.20. Information flow of EDM process simulation incorporating sustainability 81
Figure 5.21. CAM-based EDM process simulation 82
Figure 5.22. (a) MRR variation compared to circular area and (b) MRR variation across different peripherals with respect to average value [106] 84
Figure 6.1. Mold making process flow with milling and EDM processes 85
Figure 6.2. Process design dialogs with Esprit CAM 87

Figure 6.3. (a) Energy consumption in the CNC milling process with five different tool paths and (b) in the EDM process for two depths of cylindrical cavities with three current sizes 88
Figure 6.4. (a) CO2 emissions and (b) other GHGs emissions by milling and EDM operations across three different energy mixes..... 89
Figure 7.1. Future work to support collaboration and management in mold and die manufacturing 92
Figure 7.2. Integration of manufacturing phase and use phase information of molds and dies 93
Figure A.1. Windows application development environment and Esprit API 104
Figure A.2. Esprit API components..... 105
Figure A.3. Operation analysis dialog box 106
Figure A.4. Milling operation dialog box 107
Figure A.5. EDM operation dialog box 108

List of Tables

Table 2.1. Molds and dies share in product price [30] 12
Table 3.1. Energy saving potential in the discrete part manufacturing by ICT (Information and communication technology) [37] 17
Table 3.2. Simplified LCA approaches of major CAD developers 20
Table 4.1. Component Use Matrix 28
Table 4.2. GHG emissions from electricity production with different source [71] 43
Table 4.3. Green house gas emission rates for electricity generation by states. 43
Table 4.4. Comparison of two implementation approaches. 57
Table 5.1. e-Pack conditions for experiments 79
Table 5.2. Process information supported by Esprit CAM. 82
Table 5.3. Cycle time and energy consumption across different jump height 83
Table 6.1. Cycle time (sec) with different feed rates and tool path patterns in milling 87
Table 6.2. Energy consumption with different current size in EDM 88
Table 6.3. Process Comparative analysis adapted from [112] 89
Table 6.4. Comparison of milling and EDM processes 90
Table A.1. Operation analysis dialog UI components 106
Table A.2. Milling operation dialog UI components 107
Table A.3. EDM operation dialog UI components 108

Acknowledgement

First and foremost, I would like to thank my advisor, Professor David Dornfeld. He always gave me a great advice and guided me through kindly support. When I was confused with my research, with his help, I could find a way to overcome and with his encouragement, I could advance. His help made me achieve more during my academic life at Berkeley and Ph.D study.

In particular, I would like to thank Professor Sara McMains. When I come to Berkeley after a long time as a professional engineer, she helped me to get used to my late academic life as my major advisor and advised me to structure my research work as chair of my qualifying examination.

I also feel very grateful for Professor Sara Beckman. With her expertise in product development and kind and professional advice, she helped me prepare and improve both my presentation at my qualifying examination and this thesis.

I would like to express my gratitude to Professor Paul Wright. His expertise in manufacturing helped me a lot during my qualifying examination and thesis preparation. His advice also helped me prepare my first paper publication.

I would like to acknowledge all my past and current group members during my stay at the Laboratory of Manufacturing and Sustainability. They created a great work environment. Sometimes as a friend and sometimes as an advisor, they helped me have a great experience at Berkeley.

Above all, I would like to thank my wife Yunhee and my daughters Jiyoo and Minchae for their unconditional love and support. Thanks to them, I could get through my late academic life. I would also thank my mother who always wishes my happiness and my sister for their love and support.

Curriculum Vitae

1989 – 1993	Bachelor of Science Mechanical Design and Production Engineering Seoul National University
1993 – 1995	Master of Science Mechanical Design and Production Engineering Seoul National University
1995 – 2008	Engineer Samsung Electronics Co.
2008 – 2013	Doctor of Philosophy Mechanical Engineering (Minors: Electrical Engineering) University of California, Berkeley

Publications

Daeyoung Kong, Seungchoun Choi, Yusuke Yasui, Sushrut Pavanaskar, David Dornfeld and Paul Wright, "Software-Based Tool Path Evaluation For Environmental Sustainability", *Proc. NAMRI/SME* **39**, 2011

Daeyoung Kong, Seungchoun Choi, Yusuke Yasui, Sushrut Pavanaskar, David Dornfeld and Paul Wright, "Software-Based Tool Path Evaluation For Environmental Sustainability", *J. Manufacturing Systems* **30**, 241–247, 2011

Daeyoung Kong, Seungchoun Choi, and David Dornfeld, "Software Support for Environmentally Benign Mold Making Process and Operations", *Re-engineering Manufacturing for Sustainability* 279-284, 2013

Nancy Diaz, Seungchoun Choi, Moneer Helu, Yifen Chen, Stephen Jayanathan, Yusuke Yasui, Daeyoung Kong, Sushrut Pavanaskar, and David Dornfeld, "Machine Tool Design and Operation Strategies for Green Manufacturing", *Proc. 4th CIRP International Conference on High Performance Cutting,* 2010

Chapter 1

Introduction

This chapter provides background and motivation for this dissertation. The objective, approach to achieve this, and expected contribution of this research will be briefly explained. Finally, the outline of this dissertation will be briefly presented.

1.1 Environmental sustainability

Development of new technologies and advancement of manufacturing techniques has improved the standard of living and enabled many new convenient products in daily life at low cost. On the other hand, such technologies have accelerated the consumption of limited natural resources, especially fossil based fuels like petroleum and coal. Abundant consumption of resources brought another serious side effect with environmental problems like greenhouse gas emissions and water pollution. Concerns about the environmental impact, a by-product of high energy consumption, have raised environmental sustainability to become one of the important criteria for product developers. Resource efficient and environmentally benign manufacturing technology is getting more attention from product manufacturers these days.

1.1.1 Energy & resource concerns

Entering into the 21st century, increasing cost and depletion of natural resources have become a serious issue for many different economic sectors due to limited availability of the resources. Among this, dependency on fossil-based fuels is a very serious problem. While electricity is an indispensible part in daily life and many researchers are working on the topic of alternate energy sources like solar, waves, and wind, the high dependency on the fossil-based fuels has not reduced very much if at all. Furthermore, the increase of electricity consumption and production has been accelerated with growth of under-developed countries like China and India. As a result, the distinct increase in the price of energy related resources is clearly seen. According to an analysis shown in Figure 1.1, Crude oil prices have rapidly increased, rising almost 600% since 1995 [1].

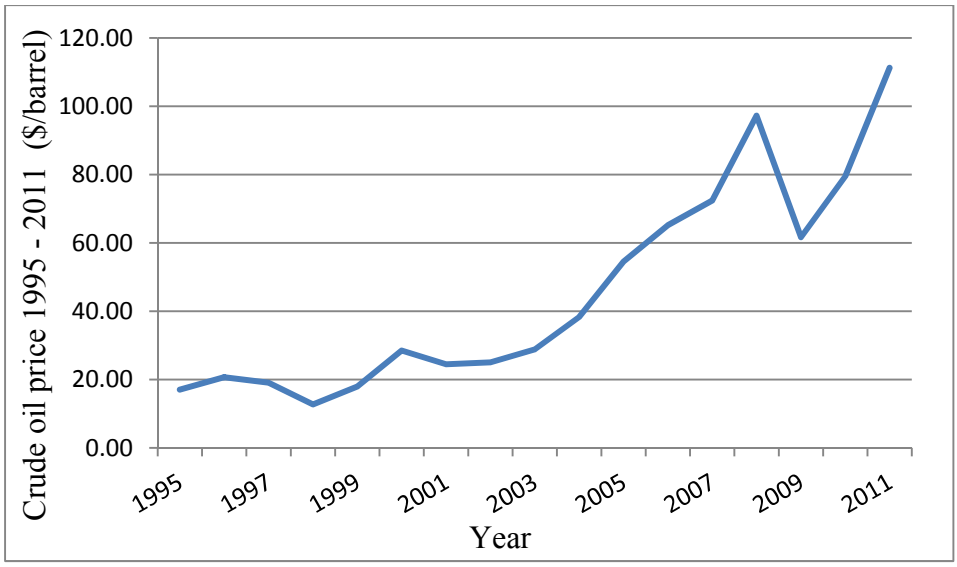


Figure 1.1. Crude Oil Price Change [1]

Because of its high dependency on pricey natural resources, US electricity production cost has almost tripled for the same period [2]. Although the increase is lessened by improved electricity-related technologies for power generation and transmission, the cost burden of electricity production is huge under the inflation of natural resource costs. This trend is getting more serious as shown in Figure 1.2. As a result, efficient electricity consumption and lower environmental impact became an important criterion in many fields from factories to distribution.

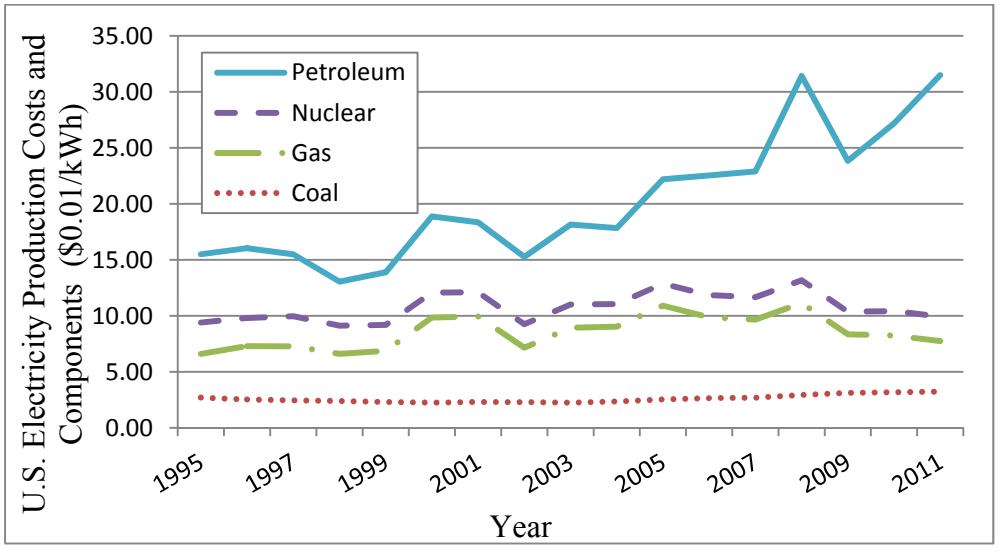


Figure 1.2. U.S. Electricity Production Costs (C/kWh) [2]

However, even with increasing cost, fossil-based fuel is still generally competitive in price compared with other clean energy sources [4]. CO_2 emissions in the US have decreased with reduced fossil-based fuel usage in recent years. However, with emissions in China and other developing countries, world concentration of CO_2 and average temperature keep increasing, as Figure 1.3 [3].

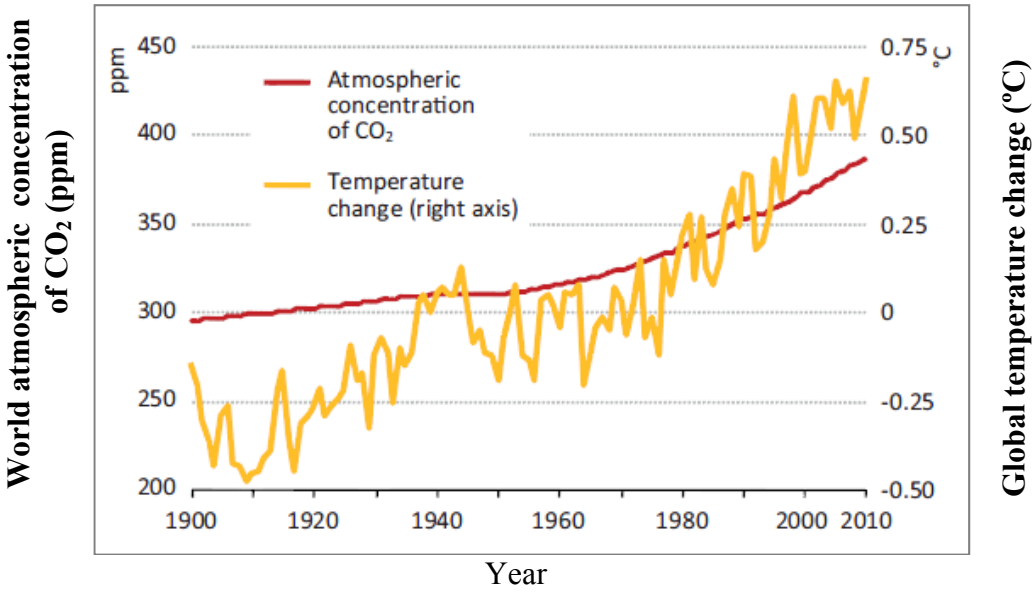


Figure 1.3. World atmospheric concentration of CO2 and average global temperature change [3]

1.1.2 Influence of manufacturing sector

With respect to energy consumption and green house gas (GHG) emissions, the manufacturing sector is known to be one of the biggest contributors among various sectors [5][6]. According to a 2007 International Energy Agency (IEA) report, manufacturing is responsible for 33% of total energy consumption and 38% of total direct or indirect CO_2 emissions as shown in Figure 1.4 [7]. Hence, without improving the manufacturing sector, the increasing environmental issues cannot be effectively addressed.

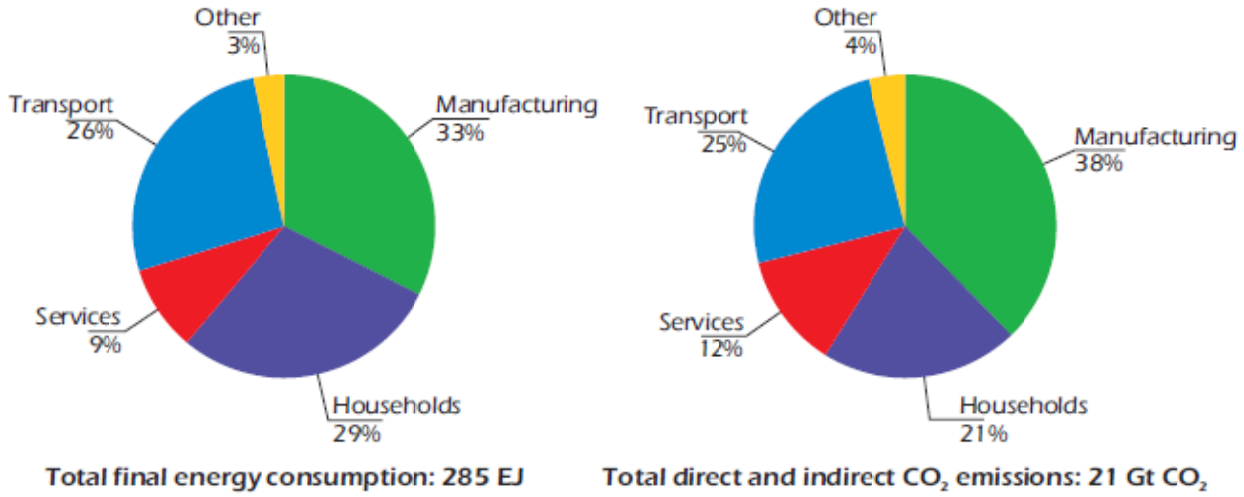


Figure 1.4. (a) Total final energy consumption and (b) total direct and indirect CO2 emissions [7]

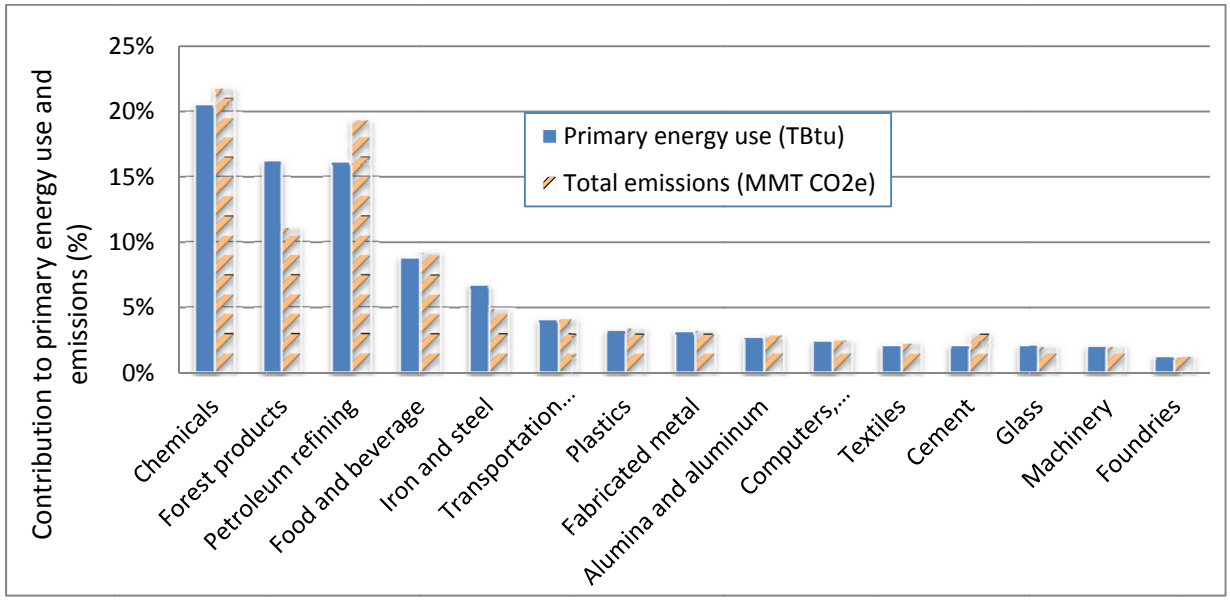


Figure 1.5. Primary energy use and emissions in U.S. Manufacturing sectors [8]

According to a report from the U.S Department Of Energy (DOE), various raw material processes are ranked as top energy users among U.S. manufacturing sectors [8]. Next to the raw material conversion processes like chemical production or iron and steel making, transportation equipment and fabricated metals are ranked high. Even considering their popularity in the market, electronics and computers ranked lower. In terms of GHG emissions, most sectors hold a similar position to that in energy use. Only petroleum refining and cement have higher comparative rank and petroleum shows the largest difference compared to other sectors. Transportation equipment and fabricated metals have similar positions for emissions as they have in energy use as shown in Figure 1.5.

1.2 Metal fabrication and the environmental impact

The increased availability of natural gas has increased competitiveness versus coal and a gas-fired combined cycle plant produces almost half the emissions per kilowatt hour than a coal-fired plant [3]. By 2005, the U.S. used 23 percent less energy to produce a dollar of goods than in 1990, the reference year of the Kyoto climate treaty [6]. With technical development, U.S. industry has reduced its carbon dioxide emissions for decades. However, compared with the EU and Japan, the U.S. is still producing twice as much carbon dioxide and needs more improvement [3].

1.2.1 Plant based manufacturing sector

In Figure 1.5, most of the top ranked manufacturing sectors with respect to consumption or impact depend on mass production facilities. Plants with large equipment are used in these sectors and the efficiency of the facilities directly leads to productivity and quality. Only small numbers of different products are produced in large amounts: e.g., through processes with complex pipe lines and different chemical facilities, different kinds of fuels, lubricants, and asphalt are produced in the oil refinery sector. The plant is built and equipped with facilities according to the required processes. Because the facilities are maintained generally through at their life span, the process design is important: e.g., facilities of chemical plant and oil refinery are expected to operate at least 10 to 15 years [9].

The manufacturing performance in this sector is improved mainly by process optimization and more efficient facilities. To effect process optimization, various manufacturing parameters are tested and evaluated for better performance. Through this procedure, optimal parameters are selected and applied to practice and maintained. More efficient facilities can be applied to improve performance but the overall process is maintained in many cases. The performance is affected by facilities rather than by operators. Operation skills are not much required and the improvement is limited under the same process and facilities.

1.2.2 Fabricated metal manufacturing sector

Industries in the fabricated metal product manufacturing sector transform metal into intermediate or end products with traditional processes like forging, stamping, bending, forming, and machining, used to shape individual pieces of metal; and other processes, such as welding and assembling, used to join separate parts together [8]. Compared with other top ranked sectors, product diversity and variation of the operating conditions in the fabricated metal manufacturing sector is huge. The machinery manufacturing sector has the same characteristics.

Products with different dimensions and designs are produced with different process plans. Optimal process parameters found for a specific product cannot generally be applied to other products due to different product specifications. Performance of various machine tools used in this sector is important in manufacturing capacity. However, different from the other mass

production sectors, manufacturing skills are also important to the productivity and quality. Because an appropriate process plan is required for the correct operation of machineries and processes, manufacturing information and process analysis are indispensible in this sector. Hence, compared with the environmental performance of the other mass production sectors, a higher possibility exists at the production operation level to improve the environmental performance in this sector.

1.2.3 Machine tool energy consumption

Metal fabrication is performed using various machine tools. Machine tools consume significant amounts of electric power during their use phase, which the European Association of the Machine Tool Industries (CECIMO) claimed to be the biggest source of environmental impact [10] in a machine tool's life cycle. Enparantza et al. showed that energy consumption cost takes about 80% of purchase price of a grinding machine according to the Life Cycle Cost (LCC) analysis [11]. Diaz et al. found that about 70% of the total emissions of machine tools result from the use phase [12]. For these, energy consumption analysis attracted many researchers in concern of environmental impact. Munoz et al. analyzed the mechanism of a material removal process and designed an integrated energy consumption model that includes process energy consumption, process rate, and waste-stream flow [13]. Dahmus et al. investigated the energy demand of individual function parts of a machine tool and found that rather than cutting energy, peripheral functions, which include computer, fans and tool change, take considerable part in energy consumption of machine tools [14].

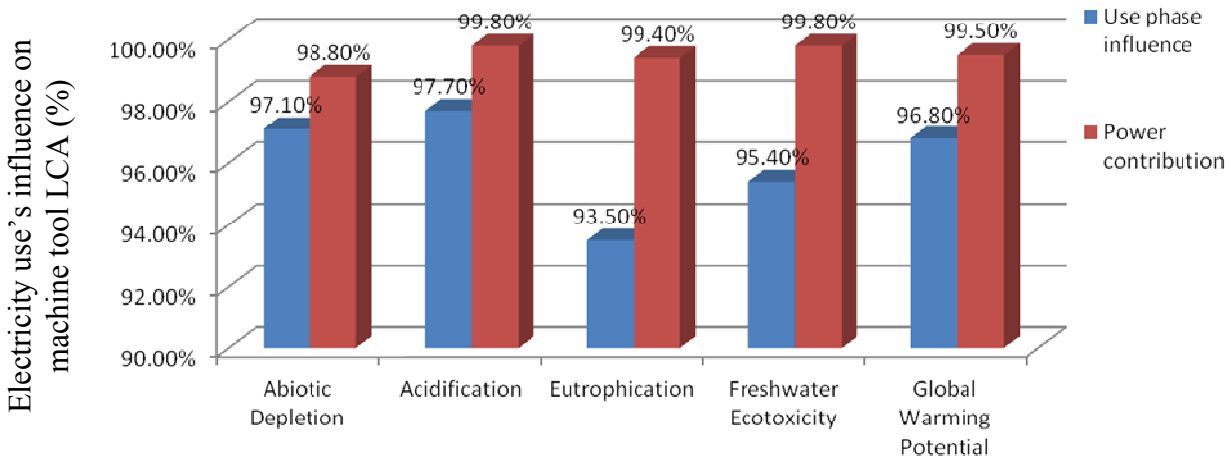


Figure 1.6. LCA results of machine tool use phase [10]

To understand the energy consumption of machine tools, various manufacturing processes have been analyzed and related models have been suggested as reviewed after. Models for injection molding [15] and casting process [16][17] have also been suggested. These models can be applied to practice with validation using statistical analyses thanks to the mass production

characteristics of the processes. Cutting processes like milling and turning processes also have been analyzed [18][19]. These cutting processes are more dynamic in practice and statistical approaches to model generation and verification cannot have a similar efficacy as with mass production technologies [20][21], Dietmair et al. introduced a model to predict energy consumption across different machining operation statuses [22].

1.3 Objective of this dissertation

A lot of information is used in metal component and product fabrication: product design, procurement, production planning, and quality control. To enable software-based simulation, early work at Berkeley included Cybercut [23] and this was extended to include basic environmental tradeoffs in follow on work [24]. Narita et al. developed an "environmental burden analyzer" with numerical data and showed how each component of Computer Numerically Controlled (CNC) machining comprises environmental burden [25]. Heilala et al. focused on the analysis of the environmental impact, automation level and ergonomics of the manufacturing system [26]. They proposed a hybrid method using discrete event simulation and analytic calculation. Shao et al. summarized the procedure of developing virtual simulation tools of machining [27].

Software-based simulation tools can be effective ways of estimating energy consumption and resultant GHG emissions if sufficiently detailed. Metal products cannot be recovered to their original state without additional processes making reliance, recycling or reuse of uncertain value. Hence, software-based simulation is more effective for assessing design and products trade-offs in case of metal fabrication. This dissertation is focusing on the molds and dies, which are typical products manufactured with metal fabrication.

Based on literature review and experimental work, various factors which influence the environmental impact of molds and dies will be considered. Through this, environmental estimation models about molds and dies will be devised and implemented as software tools. Through this, this dissertation will address the needs for environmentally benign manufacturing of molds and dies and resultant environmental friendly product development.

1.4 Contribution of this research

Despite increasing concern of environmental sustainability, the environmental sustainability remains a new concept in manufacturing practice. Many issues exist about this: diversity of manufacturing processes, incomplete standard for data assessment and communication. Insufficient software support to assess and utilize sustainability information is another barrier for manufacturing engineers to accept sustainability as a new criterion in manufacturing practice.

The research conducted in this dissertation is dedicated to the software tools for sustainable manufacturing, especially focusing on mold and die manufacturing. With CAM-based software, this research helps to incorporate academic knowledge about environmental sustainability into existing manufacturing processes and provides an effective way regarding mold and die manufacturing. Through this, existing methods were analyzed and fortified.

1.5 Outline of dissertation

The objective of this dissertation is to create a method to estimate the environmental impact of mold and die manufacturing and the development of software tools to support this. This dissertation consists of 7 chapters organized as follows.

Chapter 1 starts with the introduction and background about environmental sustainability and the impact and significance of manufacturing sectors.

Chapter 2 presents the environmental issues around mold and die manufacturing and suggests possible directions to improved environmental sustainability.

Chapter 3 focuses on information and communication technology and its potential in supporting sustainable manufacturing. Existing methods will be evaluated and current limitations will be suggested. Based on this, an alternative way of supporting sustainable manufacturing with information and communication technology will be proposed.

Chapter 4 covers the CNC milling operation as the most influential machining process for mold and die manufacturing. Limitations of existing approaches will be analyzed and a simulation model will be proposed as a more effective way. Experimental result will be provided to support the model.

Chapter 5 discusses Electric Discharge Machining (EDM) as another critical and influential process for mold and die manufacturing. The material removal mechanism of the process and related parameters will be analyzed. Based on the material removal characteristics, a method for cycle time estimation will be suggested and, based on this, a prediction model for energy consumption of the EDM process will be proposed.

Chapter 6 describes a CAM-based simulation tool for energy consumption and environmental impact estimation of mold and die manufacturing. Architecture and information flow will be explained.

Chapter 7 summarizes all the work during this Ph.D. study and discusses the future of software based approaches for mold and die manufacturing in terms of the sustainable manufacturing and product development.

Chapter 2

Mold and Die Manufacturing

2.1 Introduction to molds and dies

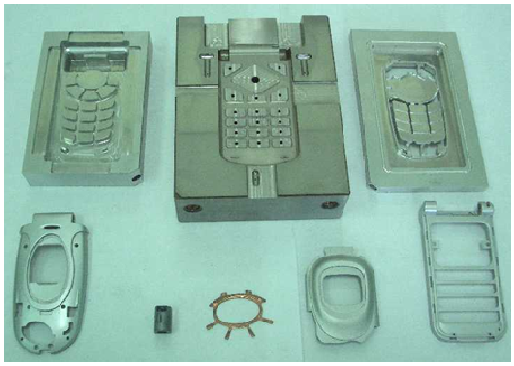
This chapter is devoted to describing molds and dies and explaining why manufacturing and use of molds and dies is important in sustainable manufacturing. Various types of molds and dies and their working mechanisms will be introduced. Information on the industrial sector for molds and dies will also be provided to help understanding why molds and dies were selected as target products in this research. Based on this information, why electricity consumption of manufacturing processes needs to be estimated for realizing environmental benign molds and dies will be explained.

2.2 Molds and dies

Molds and dies are popular manufacturing tools for mass production of design shapes. With the complimentary machined shapes of molds and dies and various mechanisms using them, different materials from metals to plastics, glasses, and rubber/polymers can be manufactured to create custom design products repetitively and with high efficiency. Because the manufacture of molds and dies is expensive and to resist the pressure and wear of mass production, molds and dies are generally produced with hardened steel, steel, or aluminium alloys. Material choice is decided based on economics driven by expected number of cycles used and related material properties and complexity of design. While hard material costs more in manufacturing, molds and dies made of such material provides a long life span to produce more products. When specific design shapes are required as components or complete products in large volume, molds and dies are indispensible and the most efficient choice in manufacturing. Hence, applications of molds and dies broadly range over products such as automobiles, consumer electronics, electric equipments, office goods, packaging containers, toys, household goods and precise optical lenses. Furthermore, as design gets more important in market competition, molds and dies of higher precision and quality became a key component in manufacturing these designed products.

Due to the popularity and various usages, many different manufacturing methods exist utilizing molds and dies. One important factor of selecting relevant methods is the material to be used. In case of plastics, injection molding is generally used. Blow molding is used for production of bottles and containers. Compression molding is used for rubber shoes, and automobile components like hoods and fenders. Injection molding is the most widely used method for consumer electronics like TV, cellphone, and computer. On the other hand, metal products are generally produced by plastic deformation by cutting or shaping. Steel pipes and beams are produced by drawing, roll forming, and extruding. Steel and other sheet metal-based curved surfaces are manufactured with forming methods. In between, low melting point metals like aluminium can be turned into complex shapes using diecasting methods similar to injection

molding but with liquid metal injected under pressure. Figure 2.1 shows two examples of the injection molds for cellphone covers and forging dies for automobile products.



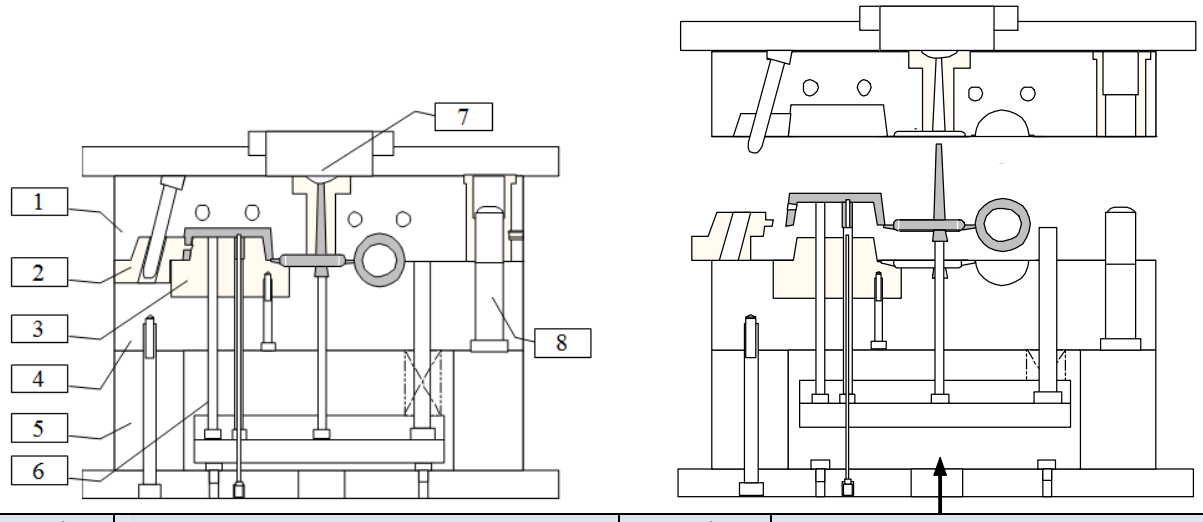
(a) Injection mold for celphone covers
[http://www.sehpre.co.kr/products/product05.html]

(b) Die for automobile cover
[Godrej tooling]

Figure 2.1. (a) Molds for cell-phone covers and (b) dies for automobile cover sheet metal body components

Based on the selected method, different structures are used for molds and dies. Figure 2.2 provides a schematic of the basic injection mold structure. As shown in the figure, besides the main core with the design shape, many different sub components or assemblies are used in the structure. Each component is manufactured with the required strength and accuracy to perform its role in the structure. While some common components are commercially available as standard parts or intermediate material, the core parts of molds and dies are different in every product and fabrication is needed for the specific design shape. In proportion to design complexity, more supportive components and structure are added to the basic structure and increase the fabrication cost. As there is large variance in cost, one mold or die can be used to produce from thousands to millions of components with the same design shape. The material alloy used in molds and dies and its properties are closely related to the number of products to be produced with the mold or die. When the required number is small, softer material can be used for molds and dies and hence, reduce production cost and delivery time.

In the example of Figure 2.2, molten plastic, called resin is injected into the mold structure which has open volume with the opposite shape to the actual products. The cavity plate, lower core, core plate and slide cores define this volume. Injected resin shown in the gray colored elements cools down and solidifies under high pressure inside the mold. After a short cooling time, finished products are ejected by mechanical force using ejector pins as shown in the example of Figure 2.2. Through this procedure, guide pins ensure the correct movement of the mold structure. This procedure takes only some seconds to several minutes in general depending on mold mechanical complexity and is repeated for mass production.



Number	Component	Number	Component
1	Cavity Plate	5	Spacer Block
2	Slide Core	6	Ejector Pin
3	Lower Core	7	Sprue
4	Core Plate	8	Guide Pin

Figure 2.2. Basic mold base structure and injection molding mechanism

2.3 Influence of molds and dies in the product development

Molds and dies are important capital goods globally traded to mass produce many different consumer goods. Mold and die technology directly affects the quality, delivery, and cost of related products. With more accurate and strong molds and dies, more products can be produced with one mold or die at controlled quality levels. Due to this advantage, products of very complex shapes can be mass produced and available at low price. Molds and dies are used for mass production in industry and the global market for these products is large and its volume has been steadily increasing. As a result, a large global market exists for manufactured molds and dies and their consumption is on the order of €65B ($97B) in 2008 [28]. The market size increased to $111.5B in 2010. Dies and molds for plastic and rubber products increased more steeply compared to other products like metal molds for the casting.

The chart below, Figure 2.3 (a), shows production values of various molds and dies. Many products are influenced by molds in various aspects of manufacturing technology. The growing cost of raw material and increasing concern about product environmental impact raised environmental sustainability to be one of the important criteria for product developers. Resource efficient and environmentally benign manufacturing technology is getting more attention from the product manufacturers. Due to the critical role of molds and dies in today's product manufacturing, the environmental impact of mold and die making is an important issue both for mold and die makers and product developers.

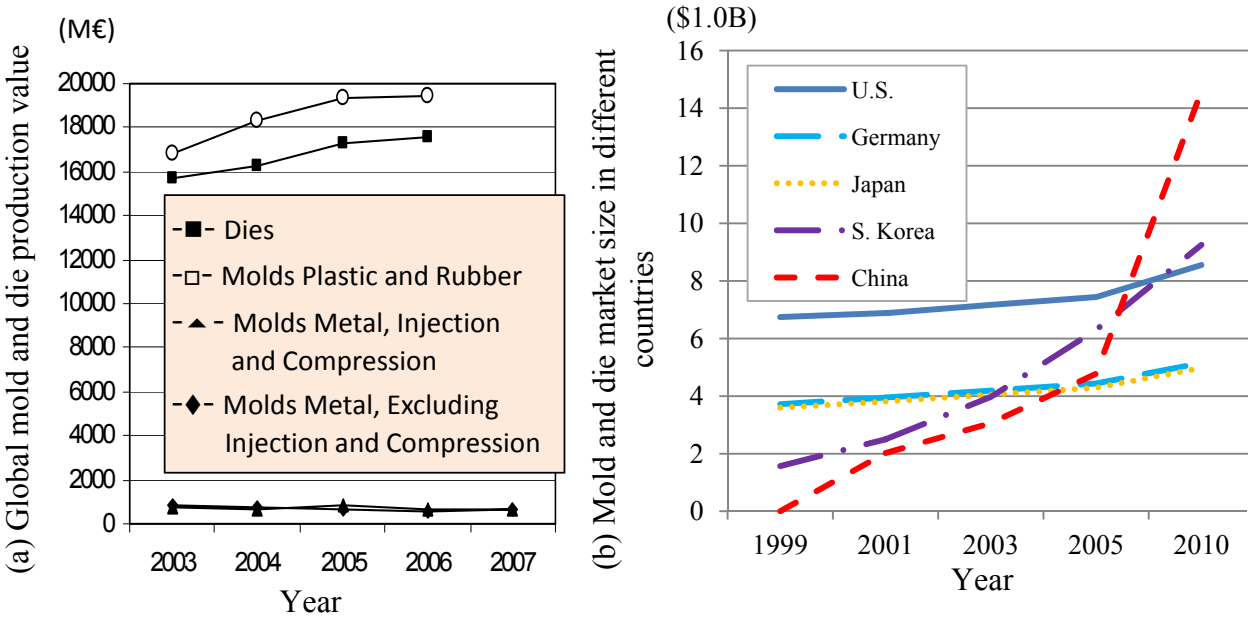


Figure 2.3. (a) Global mold and die production values and [28] (b) mold and die market needs in different countries [29]

What makes molds and dies important is the influence they play on many different products. Most commercial products are manufactured with molds and dies in part or whole. A report claimed that molds and dies form the production of 80% of commercial commodities. The following Table 2.1 shows the share of molds and dies in various products in terms of the percentage they contribute to final product price. Considering molds and dies are just tools, these numbers are not small ones for developers and that's why they are concerned about molds and dies. According to an industrial report, molds and dies are responsible for about 5% of the related products' price [30]. As a manufacturing method, this is another indicator of the important position of molds and dies.

Table 2.1. Molds and dies share in product price [30]

Product	Share of Mold/Die	Product	Share of Mold/Die
Vehicles	5%	Computer	5%
Electronics	5%	Telecom	8%
Semiconductor	5%	Mechatronics	3%

2.4 Environmental impact of mold and die

As shown in Figure 2.4, molds and dies are produced based on the interplay of many different elements. Each element contributes to environmental impact in various ways. Various materials are used for molds and dies: fixtures and cutting tools. While these materials are generally metal and recycled or reused, most coolant is wasted. Hence, efficient usage of coolant or dry machining is one important topic [31][32]. Utilities like HVAC and lighting used during production consume a significant amount of energy. Many researchers are working on the green building and building information systems. On the other hand, labor related factors affect social impact like health rather than environmental impact.

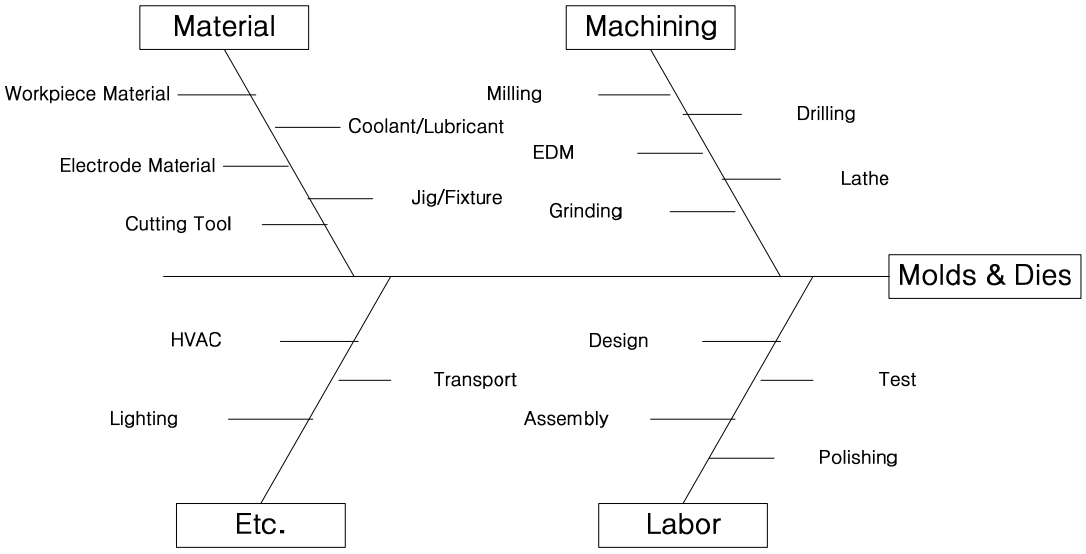


Figure 2.4. Process parameters of mold & die manufacturing process

Molds and dies are manufacturing intensive products. According to analysis of progressive dies in terms of life cycle cost, manufacturing was found to cover the biggest portion of 37% [33], Figure 2.5 (a). In the figure, other big portions are preventive and corrective maintenance. This maintenance also requires other manufacturing activities such as welding, replacing components, and additional machining. As a result, in this case, almost 82% of life cycle cost can be assumed to be manufacturing oriented. In Figure 2.5 (b) for an injection molded automotive part, mold manufacturing makes up 30% of total cost. If we exclude the use phase cost of injection molding (plastic material and injection molding process), we can assume more than 60% of cost is manufacturing oriented. Most of the material used to construct the molds and dies is responsible for only 10 to 30% of total cost and generally can be recycled, so the importance of manufacturing is certainly of concern for evaluation of the environmental impact of molds and dies.

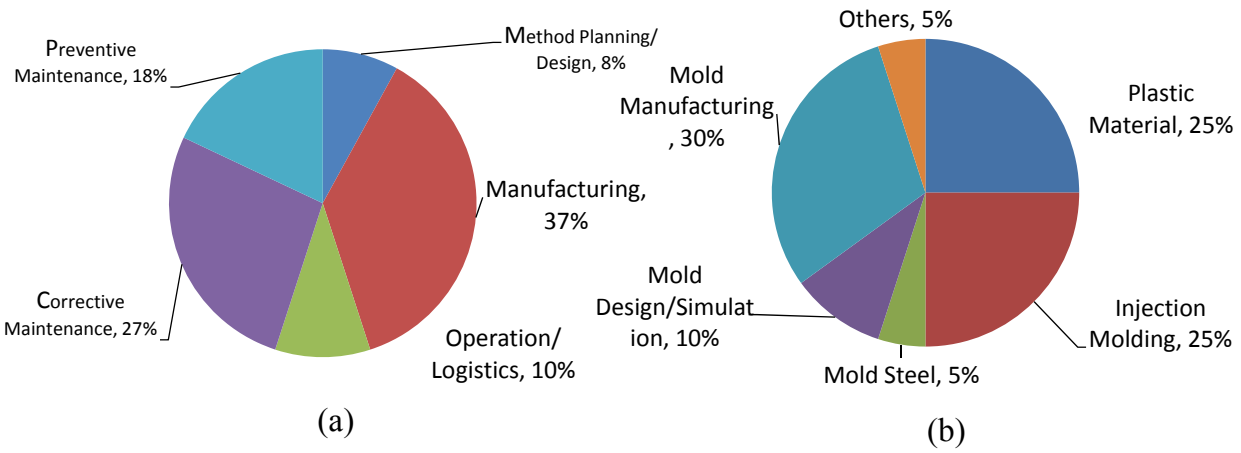


Figure 2.5. (a) Life cycle cost of progressive die [33], (b) automotive part by injection molding [34]

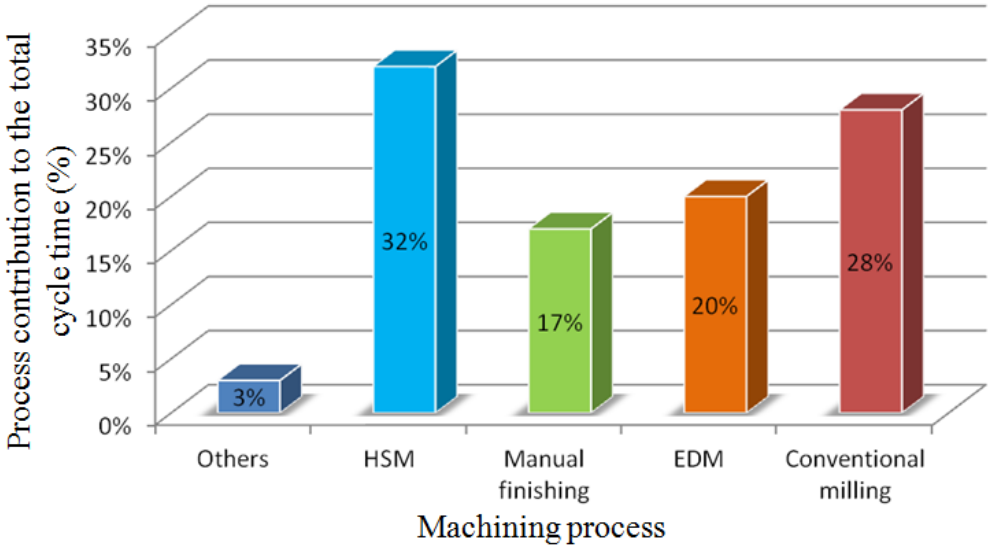


Figure 2.6. Time distribution in mold making [36]

Molds and dies are produced by various precision machining processes such as CNC milling, grinding, turning, and EDM. The mold making related industry is the biggest sales sector of some precision machine tools: more than 80% of EDM (electric discharge machining) tools are used for production of molds [35]. Hence, machining process analysis is imperative in the environmental impact assessment of mold and die manufacturing. Especially, as explained in the previous chapter, energy consumption of the machine tools is the most important part. Among various operations, CNC milling is the most popular process and EDM is expanding its usage very fast. According to a mold making time study, more than 80% of machining time in mold die manufacturing is consumed by these two processes [36], Figure 2.6.

2.5 Conclusion

Nowadays, due to increasing concern of environment and depletion of natural resources, minimizing environmental impact has been added as one of the key issues for product developers. To comply with various regulations and satisfy customer needs, developers are asked to develop more environmentally benign products. For more environmentally sustainable product development, improvement in mold and die production is indispensible. Relevant estimation of the environmental impact of molds and dies is a key factor to reduce the impact in their own market as commercial goods. Furthermore, this is more important in the much larger scope of products which are dependent on molds and dies as mass production tools. For most mold and die makers, environmental issues are another burden to address to secure business in the face of more strict environmental regulations to come. However, this can also be an opportunity to have another advantage as suppliers in this new environment and to improve their business relationships with customers.

As pointed out in the literature, energy consumption is the biggest environmental impact contributor of the machine tool. Due to the machining intensive nature of mold and die manufacturing, we may consider the energy consumption as the biggest impact contributor in the mold and die manufacturing. CNC milling and EDM were found to be the most time-consuming operations in mold and die manufacturing. While there are different cases like optical precision molds which depend as much on grinding or diamond turning for surface finishing, in most case, CNC milling and EDM do not lose the position as the dominant time consuming operations. Hence, in this thesis, these two processes and their energy consuming characteristics will be analyzed as an effective way to estimate the environmental impact of mold and die manufacturing.

Chapter 3

Information system and mold and die manufacturing

3.1 Introduction

An information system collects and stores a variety of information in a database, processes the data, extracts or creates useful information, and distributes the information to be used effectively. With development of manufacturing technology and the huge amount of available product information, information systems are now an integrated part in the current manufacturing systems. As shown in Figure 3.1, many different software tools are used for product development from design to supply chain management. For collaboration and information sharing, many PLM (Product Lifecycle Management) companies provide various information sharing platforms to integrate different manufacturing tools.

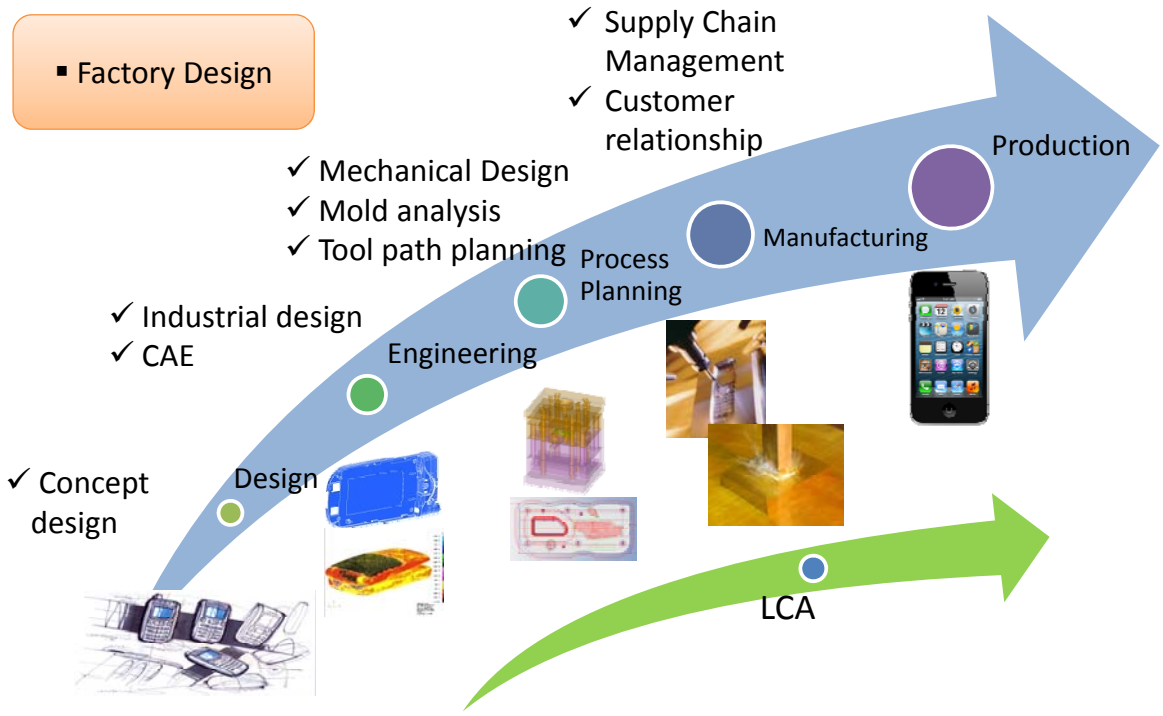


Figure 3.1. Various software tools in product development

Also, standard data interface formats like IGES (Initial Graphics Exchange Specification) and STEP (Standard for the Exchange of Product model data) are supported by different tools.

Compared to the conventional software tools, environmental sustainability is an unfamiliar criterion to product developers and software tools including this issue are not available or, if available, are not well integrated with the product development process. In this chapter, the importance of information systems for manufacturing will be covered and the current limitations of software tools related to sustainable manufacturing will be explained.

3.2 Information system and energy consumption in mold making

Mold and die making is a typical discrete manufacturing process. Various different machine tools and processes are used for mold and die making. A lot of information is generated and utilized in different manufacturing operations. While the process is composed of various operations, each operation is usually run independently. When the process flow is not managed adequately, some operations may work as a bottle-neck and the process efficiency may be lowered. Hence, to manage the complex information flow, information system support is indispensible and the efficiency of the system affects that of the manufacturing processes. The European Commission pointed out the energy saving potential of information and communication technologies (ICT) with respect to manufacturing as shown in Table 3.1. However, even with this potential, most software tools used in mold and die manufacturing, do not yet provide sufficient information, functions and requirements regarding energy consumption.

Table 3.1. Energy saving potential in the discrete part manufacturing by ICT (Information and communication technology) [37]

Process Optimization	25~30%
Optimized Logistics	16%
Integrated Process Chains	30%
Development of New Products	10~40%
Intelligent Motor Drives	20~40%
Alignment with Best Performers	15%

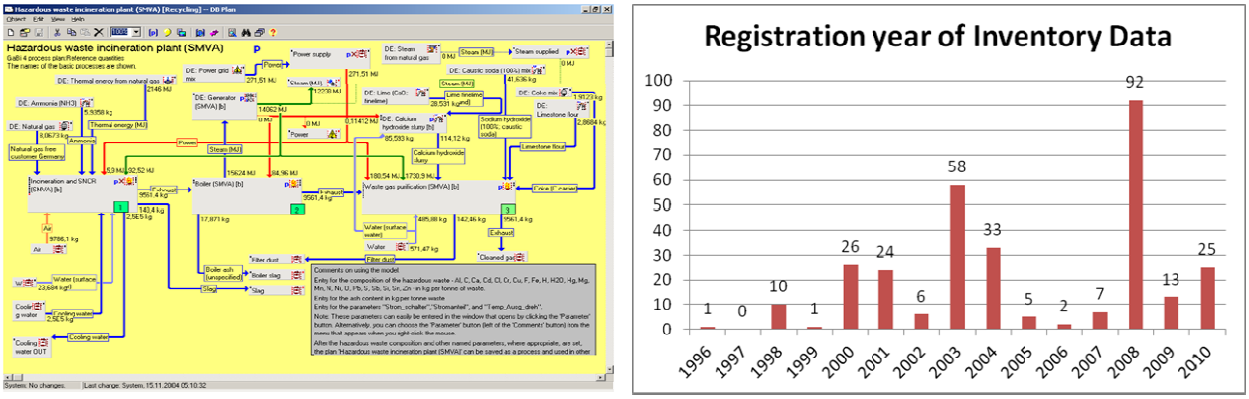
While consumers of molds and dies are generally large companies, mold and die manufacturers are usually small or medium sized companies. Many product developers require more information about molds and dies as an important part of designing and producing their products. However, due to the economic pressures or level of sophisticated training, most mold and die manufacturers do not utilize sufficient software tools. Compared to their customers, they only have limited resources in software tools and knowledge. Furthermore, most mold and die manufacturers have to manage a variety of customers all of whom may use different information systems. As a result, a lot of important information is lost and some distorted information is transmitted to customers.

3.3 Life cycle assessment (LCA) tools

Life cycle assessment (LCA) generally refers to a tool to assess environmental impact, and to calculate resource consumption of products and manufacturing processes over the entire life cycle. This requires so much information that the information system and data base is indispensible for LCA. Many commercial LCA software tools have been introduced to the market since the late 1980s and are in use for evaluation of various products. These tools differ a lot in price range, target products, interface types, and data formats [38].

Among these software tools, GaBi and SimaPro are the most dominant software tools in the market [39]. Both tools provide access to a powerful Life Cycle Inventory (LCI) database about materials and pre-defined process from various sources like EcoInvent, USA input-output, and EDIP. GaBi supports various LCA modeling and evaluation activities on the basis of material and energy flow as well as process information. With GaBi, users can design very complex models and get useful information in each unit process. On the other hand, SimaPro allows the complex processes to be analyzed as a unit process. Any update is applied to the whole system automatically and users can handle many processes within SimaPro.

Such LCA tools provide a powerful graphic interface for users to design and build a model. However, modeling specific processes is not a simple task. As shown in Figure 3.2 (a), a lot of information is needed to define the processes. Knowledge about various processes, materials, environmental impacts, and LCA itself is required for this task. A lot of data in conventional tools like CAD/CAM can also be useful in LCA tools. However, due to insufficient compatibility, most data is not directly available to LCA tools. On the other hand, LCA tools generally provide a comprehensive analysis result and it is hard to identify specific design problems or opportunities from this. Hence, it is almost impossible for designers to perform a LCA correctly under the burden of a short development time and limited resources [40]. Due to these issues, the use of LCA tools is often not effective and their greatest potential cannot be realized to improve sustainability in product design and manufacturing.



(a) (b)

Figure 3.2. (a) Gabi4 LCA Tool [PE International], (b) Registration year of life cycle inventory data in NREL database

To achieve a relevant and accurate analysis, validity of the data is very important. However, comprehensive life cycle inventory data should cover the whole life cycle of the related process and material. This inventory building is very time-consuming and continuous update is required and challenging. Figure 3.2 (b) listed the registration year of inventory data in the National Renewable Energy Laboratory (NREL) database. According to this chart, a lot of the life cycle inventory data in this database is very old dating back a decade or more. Considering the rapid change in technology development, old inventory data cannot provide the most useful information. Especially in terms of manufacturing processes, the development of machine tools and processes make the inventory data obsolete fast and the resulting analysis unreliable or inaccurate. As a result, it is hard to find useful inventory data for many current processes and, in some cases, more traditional processes.

3.4 CAD-based LCA tools

Computer aided design (CAD) is one of the most fundamental product development tools. From design shape and dimensions to the assembly structure, a lot of product information is contained in and managed by CAD tools. Major CAD tool developers are providing various tools covering a large scope of product development: concept design, product design, manufacturing, and PLM. To address the customer's requirement for environmental sustainability, many developers have been working on Eco-design capabilities, as emphasized in much literature [41][42][43], as the core part of environmentally benign product development.

Many CAD tool developers are collaborating with LCA tool developers mainly to integrate LCA tools with their conventional CAD tools. Simplified LCA (SLCA) is preferred for this approach to avoid the complexity of conventional LCA tools and to provide users with an easier interface and faster response in the analysis. Table 3.2 lists LCA-related activities of a number of the major CAD tool developers. Most tools allow users to allocate appropriate materials to their product designs and evaluate their environmental burden. While PTC is focusing material compliance around the bill of materials (BOM) information, other developers are working on including more information about manufacturing processes, factory locations transportation methods, or user locations.

CAD-based LCA tools are more convenient for users to employ to manage sustainability analysis. However, these tools depend on the product or component volume or area information based on the design shape. Complex manufacturing processes are not easy to cover with this tool. As a result, CAD-based LCA tools tend to provide underestimated impact data [44].

Table 3.2. Simplified LCA approaches of major CAD developers

Developer	LCA tools	SLCA Activity
Dassault Corp.™	▪ GaBi, ▪ SimaPro, ▪ EIME (E&E)	▪ Enovia, Catia, SolidWorks ▪ Collaboration with LCA tool developers ▪ BOM level evaluation and data exchange (IMDS, IPC1752) ▪ Material regulations (REACH, RoHS, ELV, etc.) ▪ LCA dashboard (Manufacturing process impact)
Siemens™	▪ GaBi	▪ NX, TeamCenter ▪ Collaboration with LCA tool developers ▪ BOM level evaluation (Bill of Sustainability) ▪ Material regulations (REACH, RoHS, Conflict minerals)
PTC™	▪ Synapsis Technology Inc.	▪ Windchill ▪ Acquisition ▪ BOM level evaluation (Windchill LCA) ▪ Material regulations (WEEE, REACH, RoHS, ELV)
Autodesk™	▪ Sustainable Minds	▪ Inventor, Factory design suite, Product design suite, Eco Materials Advisor ▪ Acquisition ▪ Cloud LCA

3.5 LCA tools for mold and die manufacturing

Generally, mold and die manufacturing requires a lot of information for processing and many software tools in industry support this in various ways, e.g., shape design (CAD), operation planning (CAM), and various analyses (CAE) are supported. Environmental analysis of manufacturing processes is also sufficiently complicated work that software support is indispensible for effective measure.

As explained in the previous chapters, the manufacturing sector of all sectors consumes substantial portion of energy and a lot of environmental impact is produced during the manufacturing phase. Even though the design decision is well made, poor manufacturing execution can lead to unexpected environmental problems or higher environmental impact. Furthermore, manufacturing information is necessary for the appropriate product LCA.

Conventional LCA tools are not easy to use in the manufacturing phase. A lot of information is needed as input data and the quality of the information is not satisfactory for manufacturing usage. While manufacturing engineers need very specific and accurate analysis related with cost, time and quality, many LCA tools only provide aggregated or averaged information irrelevant to specific situations. As a result, the engineers often have to design their own models when it is needed with limited resources and time. This is too much of a burden in general for engineers to

use the tool. Hence manufacturing engineers need to be able to more easily understand the existing software and have more attached functions.

CAD-based LCA tools have many of the same issues mentioned in the previous section. While CAD tools are used for designing molds and dies, it is not easy to manage the process information with the tool.

Among various tools, CAM tools are the most important to engineers for working in the manufacturing environment. However, in contrast to the activities for sustainability around CAD tools, there is no significant activity around CAM tools with respect to LCA. For sustainable product development, currently most of the software related attempts are focused on designers. The reason for this is obvious, if relevant information is provided in the design phase, the risks of harmful material usage and violation of regulations can be reduced and more environmentally benign products can be made. However, the current tools do not support the manufacturing phase effectively.

3.6 Conclusion

As explained above, information systems are imperative in successfully carrying out LCA as part of product design. However, current LCA tools are not effective in product development which is run under limited time and resources. In the case of mold making, more emphasis on process analyses is required and various operational conditions need to be considered. While many LCA tools generally use statistical estimation of manufacturing operations, there is a large gap between nominal- and actual process performance in terms of material removal rate and the cycle time. As a result, analysis with existing LCA or SLCA tools does not provide useful information yet. Through this dissertation, a software-based approach to supplement general LCA tools by handling more details of mold making processes on environmental impacts is presented.

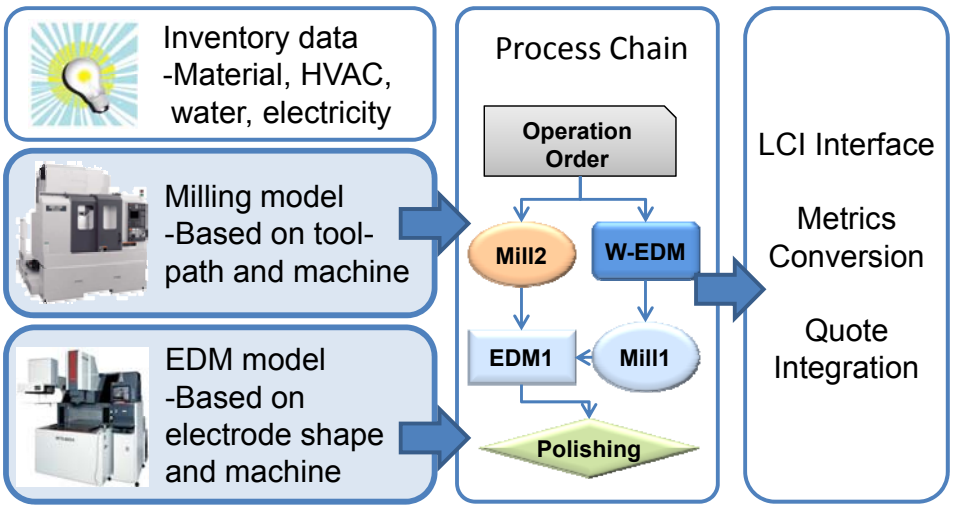


Figure 3.3. Environmental impact estimation based on two main processes

Figure 3.3 describes the approach used in this dissertation. According to Chapter 2, CNC milling and EDM operations were selected as target processes. Based on the available inventory data about energy mix or utilities and process information, which will be explained in the next chapters, an energy consumption model of these processes will be proposed and the related environmental impacts will be calculated.

Chapter 4

Environmental Impact of CNC Milling

4.1 Introduction

The computer numerical control (CNC) milling process is perhaps the most popular metal fabrication process. In the CNC milling process, workpiece material is removed by high speed rotating cutting tools and the multi-axes feed table providing precise workpiece motions along various coordinate locations. The CNC software enables the milling process engineers to manage the large amount of data for the process and fabrication of the complex geometric shapes. As a result, the CNC milling process plays an important role in current mass manufacturing. This also makes the CNC milling machine one of the top selling manufacturing machine tools in a variety of processes. In mold and die manufacturing, the CNC milling process is often the most time consuming and responsible for the major material-removal. Hence, without considering the CNC milling process, it is almost impossible to estimate or evaluate the impact of mold and die manufacturing.

Due to the inherent complexity of milling processes, simulation software utilizing computer graphics and numerical analysis has been successfully used to improve the productivity and quality of these machining operations. While such simulation software examines the operation with respect to machined surface accuracy as well as possible problems like interference between tools and workpieces or machine tools, the environmental impact of the process is not addressed in these software tools. However, because the environmental impact of the process cannot be recovered after execution of the process, environmental impact must be evaluated in simulation software to effectively reduce the impact.

In this chapter, the operating mechanism and power requirements of CNC milling machine tools will be analyzed. Based on this, existing available methods for assessing the environmental impact of the milling process will be evaluated for their applicability to CNC milling processes in mold and die manufacturing. Current barriers to the effective evaluation of sustainability in CNC milling processes will be detailed and estimation methods to address current limitations will be proposed on the basis of computer based process simulation.

4.2 Environmental impact of the manufacturing process

Machining is a complex process defined by many different factors. Various types of materials and energy are involved in the process directly or indirectly. While some of these have only trivial impact, some produce differing environmental impacts in the form of real product effects or waste. To avoid confusion and to clarify the related factors, a clear boundary definition is required to ensure an appropriate analysis or evaluation of the process. With this boundary, the input and output flows can be identified for the analysis. With regard to the environmental

impact of the process, input and output factors such as the workpiece, final products, water, lubricants, cutting tools, fixtures, electric energy, and wastes can be classified as either materials or energy. Generally, material flows can be handled with weight or mass or sometimes area but energy flows are managed in joules. In case of manufacturing processes, time is another important factor, because many factors have an impact in proportion to the related time span.

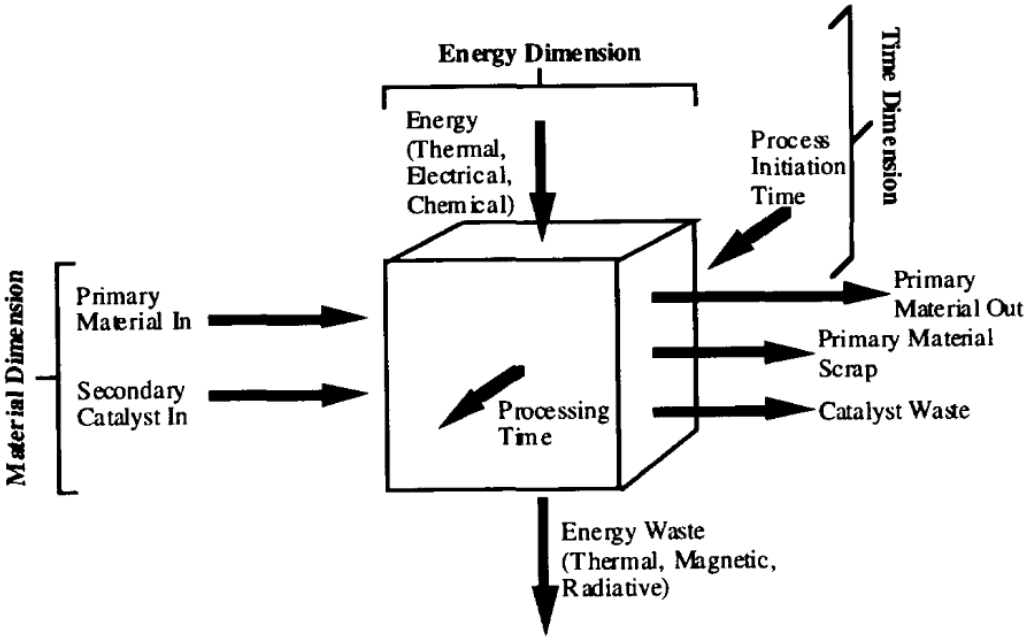


Figure 4.1. Resource flow for manufacturing processes [13]

Many LCA software tools provide an interface to define a process requiring the input and output flow of materials and energy as shown in Figure 4.1. When the related factors are filled into this process model with the corresponding amount in the appropriate specific units, the software combines the inputs and analyses for the process. Because of the law of conservation of mass or energy, this model extracts the waste which is not clearly captured in the complex process. However, as explained in the previous section, identifying related factors is difficult and some information is limited due to diversity in machine tools and variety in operating conditions. On the other hand, this can be a burden for machine tool engineers without sufficient knowledge about environmental analysis.

For a milling process, metals, like steel and aluminum are generally used as the workpiece material and transformed via machining to final product or component. Cutting tools, lubricants, coolants and fixtures are consumed during operation of the process. Final product operation and information are handled both by the manufacturer and the customer. However, the other resources are managed only inside the factory. While some information is useful and important, most information is unused or ignored without knowing its value. In this case, only limited manufacturing information is handed to product developers, which causes unsatisfactory product

analysis. To overcome this, more collaborative information handling is required and effective software support is necessary. Based on this, if this is accomplished, more effective environmental analysis would be achieved.

4.3 Breakdown of Energy Consumption of CNC Milling Machines

A number of investigations have worked at the detail of energy use in machine tools. Dahmus [14] investigated the power demands of individual functional components of a machine tool and found that the consumed energy directly related to part machining accounts for only small portion of the total consumed energy during machining. That is, while a machine tool is powered on, it wastes a large portion of the total energy even during cutting, the so called tare energy.

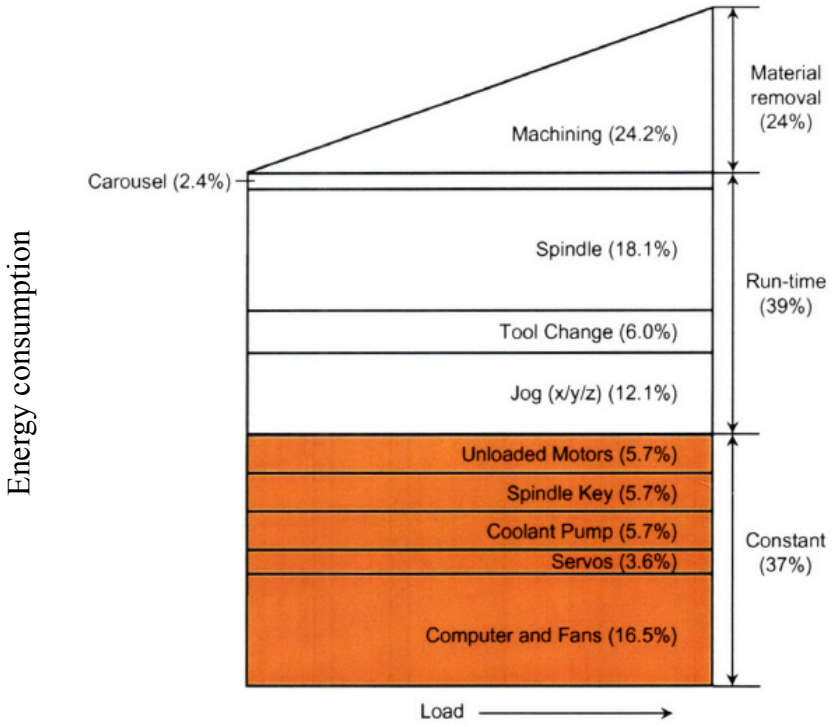


Figure 4.2. Machining energy breakdown for a 1998 Bridgeport milling machine [14]

Dahmus [14] claimed that almost 37% of the total energy is constantly wasted regardless of the machining status as colored in Figure 4.2. Since Dahmus's work about CNC milling machine tools, various machine tools were analyzed and found similar in energy consumption [22] [45] [46]. Considering this characteristic, Li et al. proposed reduced tare energy as a good way to improve machine tool energy consumption and environmental sustainability [47]. In the case of injection molding machines, Thiriez pointed out the lower tare energy in the full electric injection molding machine relative to that for other types of hydraulic and semi-electric ones

[15]. An energy monitoring system was suggested to improve the environmental performance of the manufacturing system based on the MTConnet^{TM} which enables interoperability by allowing access to manufacturing data using standardized interfaces collection from the manufacturing equipment [48].

However, such inefficiency has not been overcome yet despite some advances in the machine tool design. The tare energy still accounts for larger portion of the total energy consumption than the material removing behavior does [45]. Figure 4.2 shows that the total energy consumption during machine tool operation is composed of three different parts: constant (energy consumed by the functions that are not directly related to the machining), run-time (energy consumed by a spindle, machine axes and tool changer of a machine tool that does not change with the varied cutting conditions), and cutting energy portion (E_{cut}, energy consumed by the material removal action of a machine tool, which is dependent on the load applied to the machine tool). The cutting energy is dependent on the load applied to a machine tool and the run-time energy is dependent on the cutting parameters (feed rates and spindle rotational speed).

Because of inertia of mechanical parts of servo motors that drive a spindle and axes, it takes some time to reach a specified feed rate for the machine axes or rotational speed for a spindle. Thus the energy required to run the axes and the spindle comprises two parts: the steady state ($E_{run\text{-}time\text{-}steady}$) when the spindle motor and the axis drives keep a specified value and the transient state ($E_{run\text{-}time\text{-}transient}$) when the spindle and the axis drives accelerate or decelerate to reach specified values. It is assumed that only the feed rate and the spindle speed influence and are proportional to $E_{run\text{-}time\text{-}steady}$.

$$\begin{aligned} E_{machine} &= E_{const} + E_{run\text{-}time} + E_{cut} \\ &= E_{const} + E_{run\text{-}time\text{-}transient} + E_{run\text{-}time\text{-}steady} + E_{cut} \end{aligned} \tag{4.1}$$

Since tool paths contain motions of machine tool axes that order the cutting of the work-piece or positioning of the cutting tool relative to the work-piece, the cutting energy (E_{cut}) can be either zero when there is no load applied to the cutting tool (air cutting) or non-zero when the motion of the cutting tool or the axes results in material removal of the work-piece.

4.4 Current methods

Many LCA software tools use inventory data for specific processes which is similar to specific energy. However, the process inventory data in the software tools cannot provide reliable information in many cases due to the diversity of machine tools and their different characteristics based on complex process conditions. In much of the research, two approaches are generally used for analysis of milling operations with respect to energy consumption and environmental impact. The first one uses a breakdown of data on power demand of the machine tool and the second uses specific energy of the machine tools. In this section, benefits and limitations of these two approaches are described with respect to the estimation of the energy consumption of machine tools in mold and die manufacturing.

4.4.1 Power demand information for CNC milling components

As explained in section 4.3, machine tools consist of many different components and a major portion of the operating energy is consumed irrespective of the operating status, that is, they have high tare requirements. Energy consumption of machine tools is the summed value of the consumed value for each machine component. Among these components, many components were found to consume energy in proportion to the working time of the component. This allows the power (energy consumption per unit time) demand of such components to be used as inventory data for determining operational consumption.

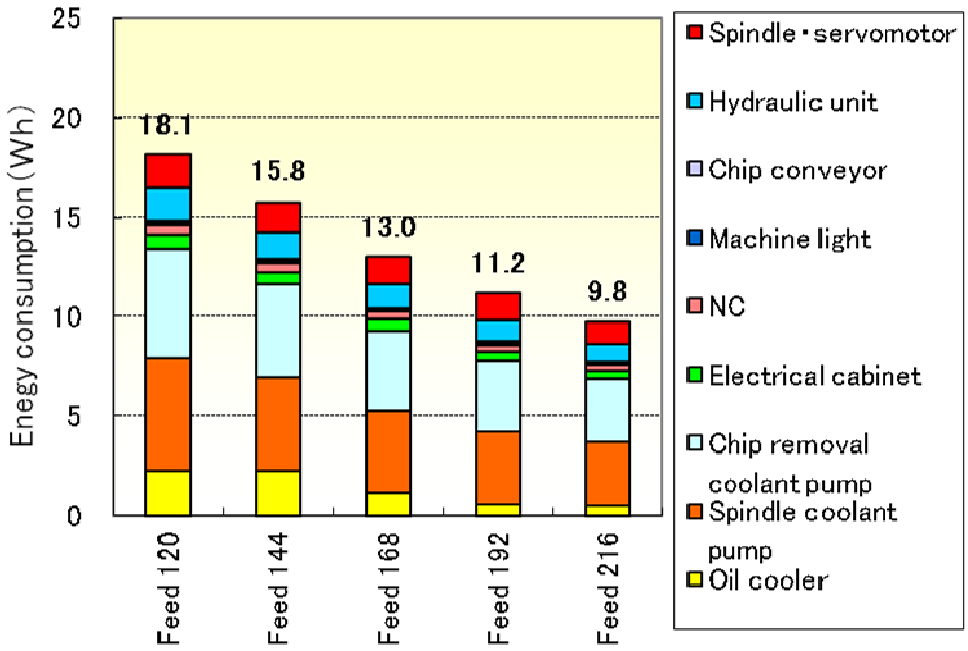


Figure 4.3. Variation of energy consumption over a range of different feed speeds [46]

To do this, identification of the components which have this time proportional power demand characteristic is required. For evaluating a specific operating condition, one can change the time related parameter and measure the energy variance to determine this behavior. For example, in Figure 4.3, different feed rate conditions were applied to the same tool paths with the same spindle speed and the energy consumption to complete each corresponding operation was measured.

The energy consumption directly related to material removal is indicated as either spindle or servomotor in red color. This is only a small part of the total energy consumption in all the cases. The values under different feed conditions are almost the same. On the other hand, due to the feed difference, the running time of the machine is different in each case and many of the high power demanding components of the machine result in an inverse-proportionality with increasing energy consumption to the feed conditions: lower federate and higher consumption.

One important task to enable use of this inventory data for energy estimation is classification of different operation modes. These modes are defined by specific operation characteristics and may be different based on the machine tool usage. From conventional modes of stand-by, idling, and machining [45] to more process specific modes [15] [22] [49], definition of the modes is a matter of choice for users. With the classified modes, corresponding components can be allocated to each specific mode: e.g., electrical cabinet and NC in the stand-by mode of milling machine tools. Based on this, a relation matrix such as an example of Table 4.1, can be made for each mode and related power demand of the components. This matrix shows the active components for each operating mode: e.g., only light and NC components are active in stand-by mode. Using this matrix, energy consumption of machine tools in each mode can be calculated by multiplying corresponding use time and the component.

Table 4.1. Component Use Matrix

	Stand-by	Idle	Machining
Light	O	O	O
NC	O	O	O
Spindle	X	O	O
Feed	X	X	O
Load	X	X	O

4.4.2 Specific energy of CNC milling process

Manufacturing processes include many different input or output factors. While electricity is a major factor in the environmental impact of manufacturing processes, it is also important to consider the other impacts of input materials and resources. However, it is not easy to compare the impacts of different type of inputs. To effectively incorporate both sides of material and energy resources together, Gutowski proposed the use of exergy, which is the potential of material to do work, in process evaluation. This simplified two different types of process factors within a conceptual value. Specific energy consumption is suggested as a metric to evaluate and compare the environmental performance of manufacturing processes. The specific energy of processes is defined as the energy consumed per unit removal volume in the following equation (4.2):

$$E_{spec} = C_1 + \frac{C_2}{MRR} \quad [J/mm^3] \qquad (4.2)$$

where C_1 is the specific energy of the process with dimension of [J/mm^3] and C_2 is fixed energy consumed to maintain various auxiliary components per unit time with dimension of [J/sec]. With this equation, the specific energy of the process can be estimated with the material removal rate (MRR) and overall energy consumption can be estimated with expected removal volume.

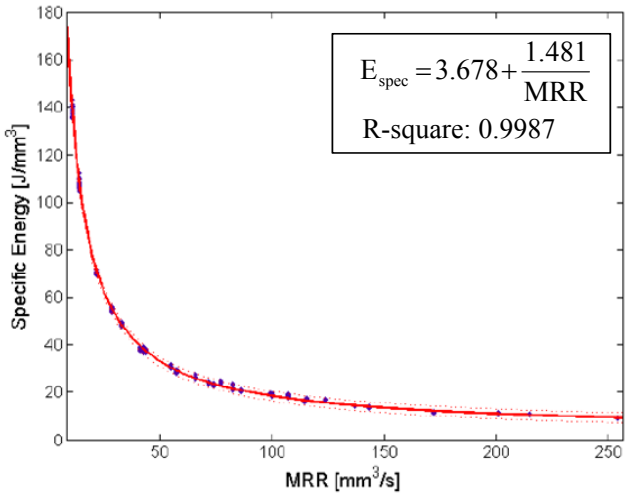


Figure 4.4. Specific energy as a function of MRR for Mori Seiki NVD 1500 [50]

This equation is applicable to any process with respect to MRR. Hence, various unit processes can be compared in terms of specific energy regardless of the process type and machine tool characteristics. As the Gutowski graph in Figure 4.5 shows, different processes can be used as benchmarking reference with specific energy [51].

On the other hand, the limitation of this equation is apparent because two coefficients C_1 and C_2 are effective only in specific ranges of operating conditions. As Draganescu et al. pointed out, the specific energy of the process may vary across a large range and the value can be useful only when the value and operating parameters are within an appropriate range [52]. However, this is not a condition which is easily satisfied. C_1 is a machining dependent value which is affected by MRR, cutting tool shape, and material property. When there is not much variation in the operation conditions, a statistical average of C_1 would give useful information. However, if the variation is large, C_1 is not easy to define and some uncertainty cannot be avoided.

The second coefficient, C_2, is a machine dependent value which is defined by the components with a fixed power demand. C_2 can be defined by the fixed power demands during a machining operation. However, C_2 is not independent of the operating conditions, since the power demand of the spindle is directly proportional to spindle speed [49] and C_2 is affected by the power demand. Furthermore, the specific energy equation is dependent on MRR and only effective during machining. As detailed in Table 4.1, there are other operation modes which consume energy for auxiliary components. While substantial energy is consumed in idling or standby modes, this approach cannot be applied to such non-productive modes. Another limitation is for rapid traverse modes during the machining operation. Milling tool paths are composed not only of cutting tool paths but of rapid traverse motion between cutting segments to increase productivity. These paths do not contribute to material removal but consume a lot of energy. Hence, depending on the time wasted for rapid traverse motion in a cutting program, equation (4.2) may provide very different outputs.

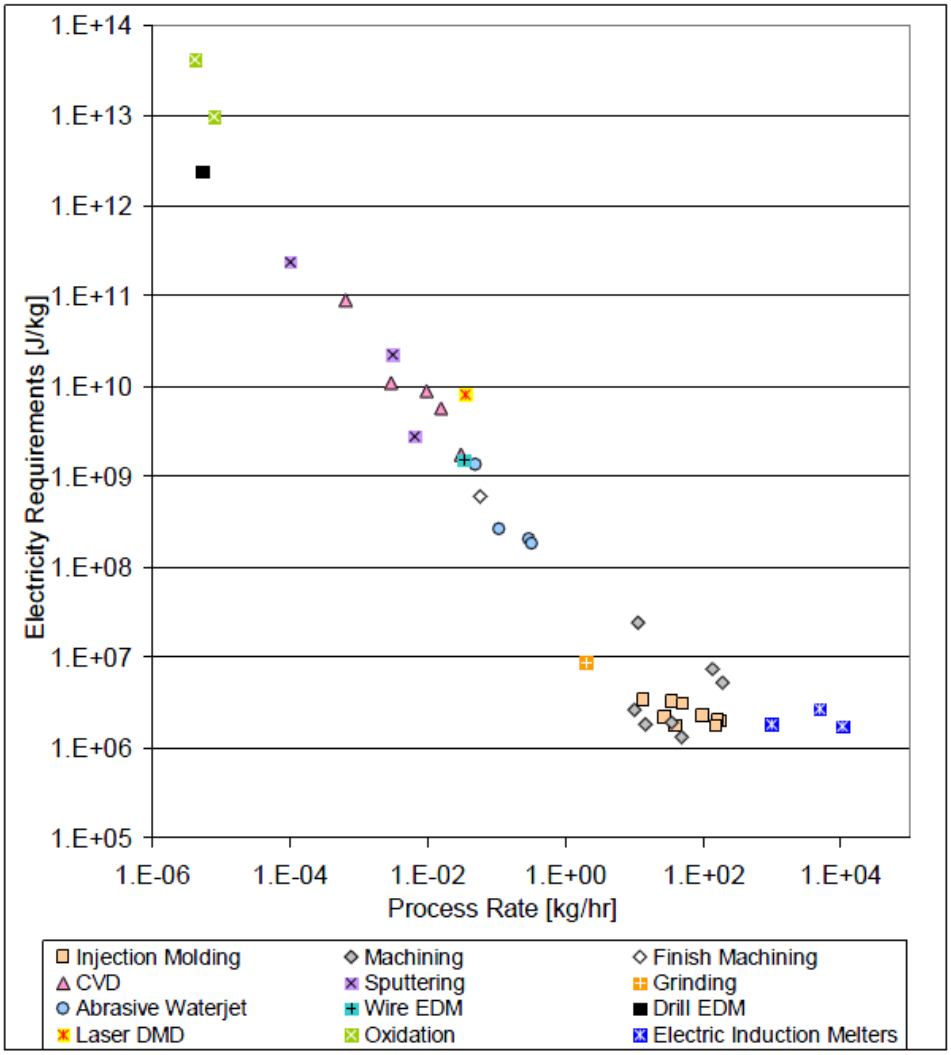


Figure 4.5. Specific electricity requirements for various manufacturing processes [51]

To overcome the limitation of the specific energy method, Diaz et al. suggested segmentation of the milling process into similar evaluation programs and then applying the corresponding MRR to each subdivided interval [50]. This approach improves the estimation of energy consumption of the process by allowing variable MRRs through the process. Kara et al. further distinguished the equation by lubrication conditions of dry and wet cutting with different C_1 and C_2 coefficients [53]. These methods reduce the uncertainty of depending on one specific condition and the specific energy method may provide more accurate estimation. However, when the operating conditions vary over a wide range, these methods cannot avoid some uncertainty.

4.4.3 Limitation of current methods

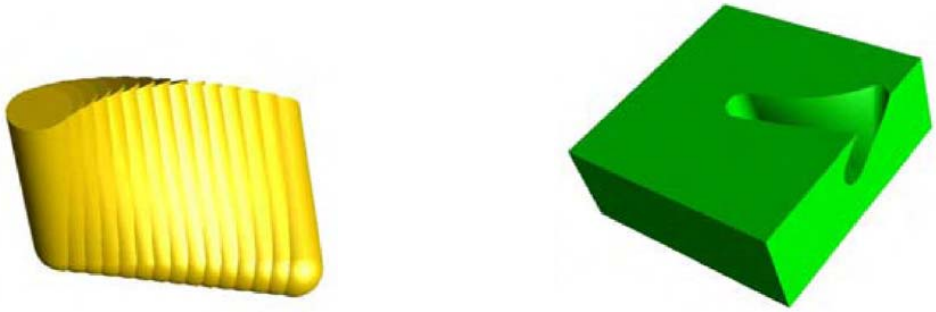
The two popular methods detailed above can be used to analyze the existing process and provide useful information when the process condition is statistically stable and variation is

small. Therefore, many mass production processes can be considered as good applications for this approach. Li et al. showed a good example of this in the case of an extrusion process chain [54]. However, both methods are based on specific operating conditions and have limited reliability except within a small range. Because the operating conditions in mold and die manufacturing have a wide range of variation, estimation based on these two popular methods will have limited reliability as process design information. Hence, to satisfy mold and die makers, more process specific evaluation is needed which is available in various process conditions.

With respect to stand-by mode energy consumption, power breakdown data can be used for a process energy inventory. If an appropriate time monitoring method is used for each machine tool, the stand-by mode energy consumption of the machine tool can be calculated with this inventory for each corresponding time span. Radio-Frequency Identification (RFID) is suggested as an effective monitoring device for such operations [55]. Considering the time and energy wasted in stand-by mode, the need for a reliable monitoring system would be apparent. However, even with such devices, the variation of cutting process is not easy to detect.

4.5 Cutting Power of Milling Process

In the milling process, material is removed from a workpiece, machine or fixture fixed to the table by a cutting tool which rotates at high speed. Vertical milling tools have no restriction in cutting direction, unlike many other processes like turning, drilling and broaching. A rotating cutting tool can sculp out volume by moving in any designed direction and fabricate various shapes following the paths. Generally cutting tools in the milling process have multiple cutting edges and various shapes designed for specific purposes. With the development of cutting tools and milling machines, various different types of milling operation have been introduced: face milling, profile milling, cavity milling, slot milling, thread milling, and so on.



(a) Tool swept volume with 5-axis motion (b) Machined part with the swept volume

Figure 4.6. Visualized (a) tool swept volume and (b) machined workpiece in milling operations [56]

While there are many different types of milling operations and cutting tools, the machined surface geometry in these milling operations is defined mainly by the cutting tool shapes and tool-paths. The cutting tool of a specific shape following a defined tool path sculpts a closed

volume called the tool swept volume. In the milling process, the volume of removed material is the intersection of tool the swept volume and the workpiece as shown in Figure 4.6 (b). Many NC simulation tools simulate the milling process and aid in finding any geometric problems by comparison of this swept volume with the designed shape. While more complicated coordinate information is used in 5-axis milling operations as described in Figure 4.6, only 3-axis milling will be handled in this thesis.

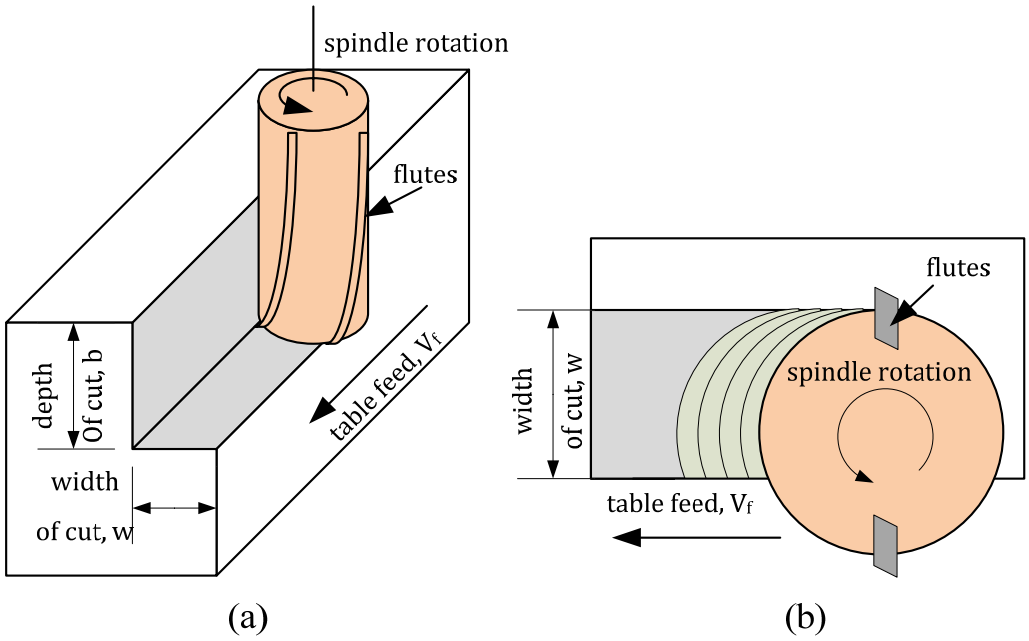


Figure 4.7. Geometric schematic of the vertical milling operation (climb milling) (a) isometric and (b) top view

In a 3-axis milling operation, tool paths are composed of a series of line or arc segments. The removal volume for each segment can be expressed by the cutting tool shape and the operation parameters of depth of cut, and width of cut. Depth of cut is the vertical distance of the tool below the workpiece and width of cut is the width of the tool engagement to the workpiece. Figure 4.7 describes this material removal relationship in a face milling process. In this configuration, MRR for unit time can be expressed by equation (4.3):

$$\mathrm{MRR}_{\mathrm{mill}} = w \cdot b \cdot \mathrm{V_f} \quad [\mathrm{mm}^3/\mathrm{sec}] \qquad (4.3)$$

where w is width of cut, b is depth of cut, and $\mathrm{V_f}$ is table feed speed defined as the tool movement speed relative to the workpiece.

The cutting force is the most fundamental contributor to the power demand of a milling machine during machining. The milling tool generally has multiple cutting edges on the end as well as the periphery, which are called flutes and described in Figure 4.7. Because the cutting mechanism is intermittent due to the engagement and disengagement of the cutting edges with each rotation, the tool cutting force is not constant with tool rotation. However, considering the high speed rotation, a statistical cutting force model would be effective for process simulation with regard to energy consumption. Among many different expressions for cutting force, specific cutting force and contact area are two major parts of the equation. Specific cutting force is dependent on material properties because it is related to the shear stress of the material. The cutting force is proportional to contact area. Hence, the cutting force can be simply defined as in equation (4.4).

$$F_t = S \cdot A \quad [\mathrm{N}] \tag{4.4}$$

where, S is the specific cutting force and A is the tool-workpiece contact area. This relation can also be modified with more details in terms of cutter shape, rotation speed, and feed speed.

Similarly, when the cutting tool removes material along the tool path, the cutting energy requirement can be evaluated by considering forces acting on the cutting tool. Using forces evaluated from orthogonal cutting theory, the energy consumption during material removal by a single rotation flute cutter that is engaged in a work-piece with depth of *b* and width of *w* can be approximated as:

$$E_{spindle} = K_{spindle} \cdot w \cdot b \cdot f_t \tag{4.5}$$

where $K_{spindle}$ is the coefficient that represents the specific cutting energy and f_t is feed per tooth. Accordingly, the average power demand of the spindle with n rotations during the cut by a z-flute cutter is:

$$P_{spindle} = z \cdot n \cdot E_{spindle} = K_{spindle} \cdot w \cdot b \cdot f_t \cdot z \cdot n \tag{4.6}$$

If chip size effect is considered these relations can be written as:

$$E_{spindle} = K_{spindle} \cdot w \cdot b \cdot f_t^{1-p} \tag{4.7}$$

$$P_{spindle} = K_{spindle} \cdot w \cdot b \cdot f_t^{1-p} \cdot z \cdot n = K_{spindle} \cdot w \cdot b \cdot v_f^{1-p} \cdot z^p \cdot n^p \quad (4.8)$$

where p is a fitting constant that is determined empirically [57].

Table feed drives also contribute to the power demand of the cutting process. However, the power demand for table feed is relatively small [58]. According to an experimental work to compare the power demands of the spindle and feed drives, the power demand of the spindle unit is much larger than that of the feed drives in a range from twice as large in rapid traverse to 15 times as large in effective machining [59]. Hence, the power demand of the cutting process can be approximated as [57]:

$$P_{cut} = P_{cut_spindle} + P_{cut_feed} \approx P_{cut_spindle} = K_{cut} \cdot w \cdot b \cdot v_f^{1-p} \cdot z^p \cdot n^p \quad (4.9)$$

where v_f is the feed rate, n is the rotational speed of the spindle, w is the width of cut, b is the depth of cut, z is the number of flutes of a cutter, and p and K_{cut} are empirically determined fitting constants. During the cutting process, the mechanical power required for the spindle unit is defined as follows [60]:

$$P_c = \frac{\pi}{30} \cdot n \cdot T \quad (4.10)$$

where T is torque. For a change in torque during machining, the spindle motor power follows a linear relationship with the increase of torque.

4.6 Acceleration and Deceleration

The tool path segment length and orientation influence the machining cycle time. Siller et al. compared actual and ideal cycle time for high speed milling of surfaces of different complexity [61]. According to Figure 4.8, as the complexity of the surface increases, actual machining takes more time compared to the ideal time. Siller et al. considered how an average segment length and frequency of paths affected this cycle time variation [61]. Surfaces shown in Figure 4.8 have the same machining area but have different complexities: the most complex surface is composed of 100 sub-surfaces but the simple one is the single surface.

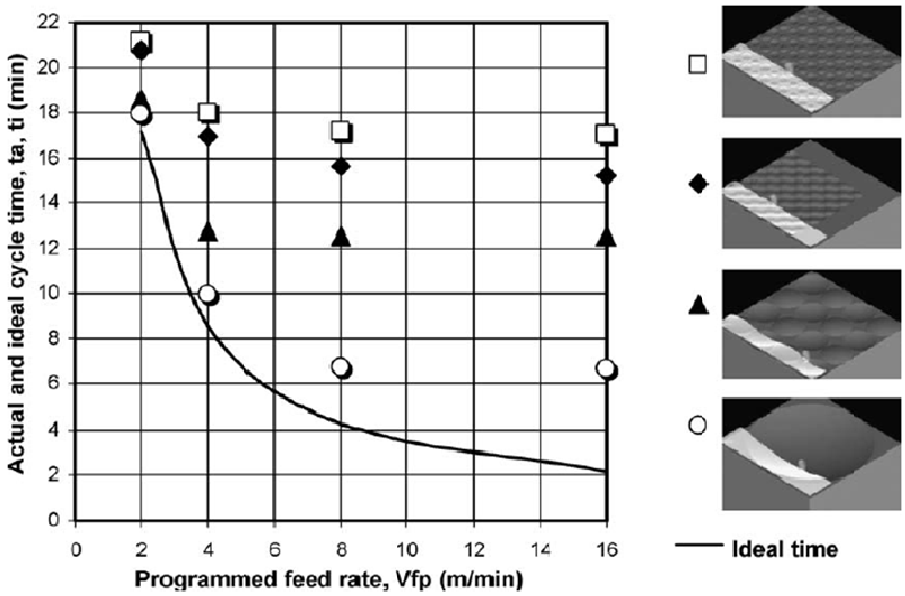


Figure 4.8. Impact of surface geometric complexity and programmed feed rate on the actual cycle time during HSM [61]

Rangarajan et al. [62] showed that a short segment length of a tool path causes a longer cycle time and thus an optimal tool path strategy exists that minimizes the cycle time. It also implies that the tool path strategy is related to the energy required to produce a product because shorter cycle time can reduce the fraction of the constant tare energy. On the other hand, Coelho et al. claimed that an empirical value of machine response time is approximately fixed and that the segment length is limited to satisfy constraints of sufficient response time [63]. All of these observations point out the need to consider the acceleration and deceleration of axes movement as influential factors for accurate estimation of the cycle time in CNC milling processes.

Regarding feed rate, there are three types of acceleration profiles: exponential, linear and bell-shaped curves [64] [65]. Among these, the bell-shaped curve provides the best performance while an exponential curve provides the worst. Besides performance, machine tool designers consider controllability of and shock on the machine tools in selecting relevant profiles. In this analysis, the linear curve profile was selected for efficient handling of the relationship between feed rates and position of the axes during machining (Figure 4.9). Maximum acceleration and deceleration were assumed for each axis.

Figure 4.9 shows two different cases of axis movement that involve acceleration and deceleration. Figure 4.8 (a) describes a case where a tool path segment is long enough for a given feed rate that the specified feed rate is reached after acceleration and the feed rate becomes zero after deceleration. Figure 4.8 (b) shows a case where a tool path segment is short for a given feed rate, so that the specified feed rate cannot be reached because the combined time required to accelerate and then decelerate the table is longer than the time to travel the tool path segment.

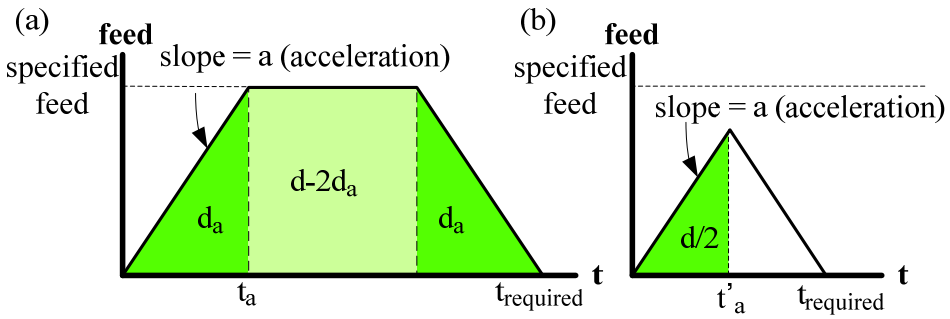


Figure 4.9. Acceleration and deceleration of machine tool axes to reach a specified feed rate

In the case of Figure 4.9 (a), the time required to accelerate to the specified feed and the movement length during acceleration are described in the following equations:

$$t_a = f / a \tag{4.11}$$

$$d_a = \frac{1}{2} a \cdot t_a^2 \tag{4.12}$$

$$t_a = \begin{cases} 2t_a + \dfrac{d - 2d_a}{f} & (d \geq 2d_a) \\ \sqrt{2t_a \cdot d / f} & (d < 2d_a) \end{cases} \tag{4.13}$$

$$t_{total} = \sum_{i-1}^{n} t_{required_i} \tag{4.14}$$

where $t_{required}$ is the time required to run a block of command of NC code, d_a is the distance axes travel during t_a, d is the total distance of travel of axes by a block of command, and f is the specified feed rate.

Since the tool movement length corresponds to the area under the curve, a longer segment induces a higher average feed rate for a specified feed rate. It implies that the cycle time can be reduced by using longer tool path segments, decreasing the energy consumption for such a movement. Moreover, since additional energy is required to accelerate or decelerate a mass, the acceleration or deceleration itself increases the energy demanded to execute a specified tool path segment.

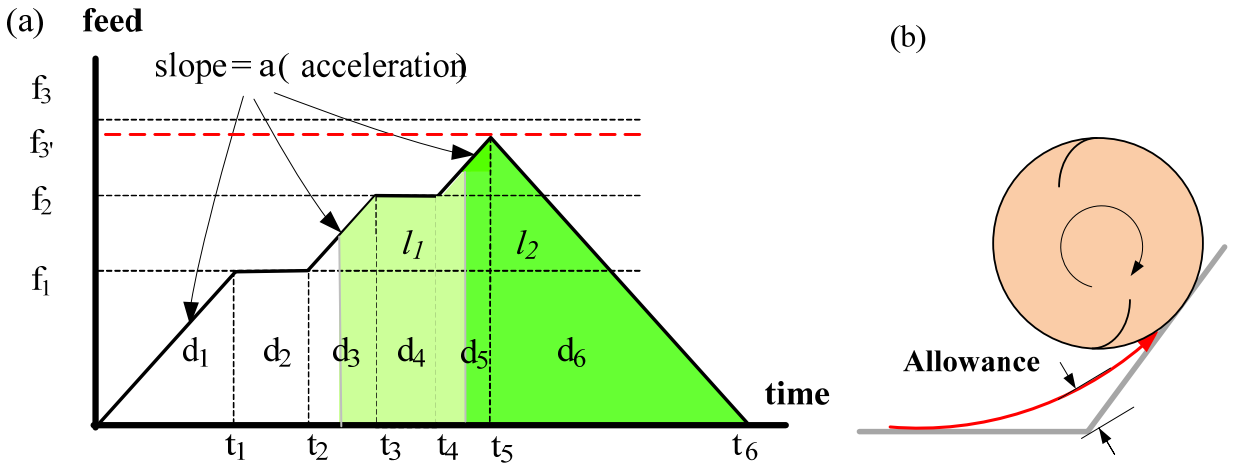


Figure 4.10. (a) Acceleration and deceleration of machine tool axes with small direction change, (b) position discrepancy in tool trajectory

High speed milling is popular in many applications with the benefit of higher performance in machining and finer quality of surface. While the feed changes dramatically and the machining performance decreases in cases of adjacent tool path segments with huge directional changes, tool paths used in high speed milling are smoothly connected and the related angular deviation is very small. Hence in many cases, the feed profile of high speed milling is different from Figure 4.9. Instead, the feed profile looks more like the connected diagonal shapes shown in Figure 4.10.

In the profile in Figure 4.9, the feed speed to one axis in the next segment is much different and deceleration is almost always needed to maintain the appropriate motion. Whereas, in Figure 4.10, two adjacent tool path segments have different feed speeds in one direction but both the angular difference and the required feed speed change are very small. Hence, the feed profile for one segment is often composed of only one of acceleration and deceleration unlike the one in Figure 4.9. As a result, very short time is spent for acceleration or deceleration in this profile, which allows the machine tool to maintain the specified high feed speed during machining. In this case, acceleration or deceleration is decided directly by two feed speeds. Hence, acceleration/deceleration time and distance are expressed as:

$$t_{trn} = t_e - t_i = \frac{\Delta f}{a} = \left| \frac{f_e - f_i}{a} \right| \tag{4.15}$$

$$d_{trn} = \left| \frac{f_e + f_i}{2} \cdot \frac{f_e - f_i}{a} \right| = \left| \frac{(f_e + f_i) \cdot (f_e - f_i)}{2a} \right| \tag{4.16}$$

where t_i, t_e, f_i, and f_e are start time, end time, start feed, and end feed of transition respectively. Hence, t_{trn} and d_{trn} are the transition time and distance. The transient time for

acceleration or deceleration can be assumed to be equally divided for each adjacent path segment. In this example, three different feed values are related. When the feed changes from f_1 to f_2, sufficient time is allowed for acceleration. However, the l_2 segment is not so long enough for acceleration that $f_{3'}$ is used instead of f_3. With equation (4.15) and (4.16), time and distance in this profile can be expressed as:

$$d_3 + d_5 = \left|\frac{(f_2 + f_1)\cdot(f_2 - f_1)}{2a}\right| + \left|\frac{(f_{3'} + f_2)\cdot(f_{3'} - f_2)}{2a}\right| \tag{4.17}$$

$$d_4 = l_1 - \frac{d_3 + d_5}{2} \tag{4.18}$$

$$d_5 + d_6 = \left|\frac{f_{3'} + f_2}{2}\cdot\frac{f_{3'} - f_2}{a}\right| + \frac{f_{3'}^{\,2}}{2a} = \frac{2f_{3'}^{\,2} - f_2^{\,2}}{2a} \tag{4.19}$$

$$f_{3'} = \frac{1}{2}\left(f_2 + f_3 \pm \sqrt{4a\cdot l_2 - (f_2 - f_3)^2}\right) \tag{4.20}$$

$$\Delta t_1 = \frac{f_2 - f_1}{2a} + \frac{f_{3'} - f_2}{2a} + \frac{d_4}{f_2} \tag{4.21}$$

$$\Delta t_2 = \frac{f_3}{2a} + \frac{f_{3'} - f_2}{2a} \tag{4.22}$$

This acceleration and deceleration avoid zero feed and increase the performance of the machine tool. However, this non-stopping motion decreases positional accuracy. As shown in Figure 4.10 (b), two adjacent segments are connected with a smooth small arc which does not pass the specified geometric location, the end of the tool path segment and the start of the next segment. The distance between actual and designed paths is considered a machining error and the value is controlled to be smaller than some positional allowance. If this allowance is set to a value near to zero, the feed profile approaches that of Figure 4.9. If the feed speed is too high to meet this allowance, the actual feed speed is lowered to the value which satisfies the allowance. This implies that small arc tool paths may be machined with a lower feed speed condition than designed.

Considering the feed profiles explained in Figures 4.9 and 4.10, the influence of the path segment length on the actual feed speed is apparent. Acceleration and deceleration keep the actual feed speed lower than the nominal speed and decrease the accuracy of estimation in various milling operations including the cycle time and energy consumption. The discrepancy between the actual and nominal feed speeds becomes clearer with shorter lengths of tool segments. Figure 4.11 shows the difference in time estimation simulated by the diagonal feed profile, for example, segment d1 in Figure 4.10 (a). In this graph, different feed speeds and segment lengths were examined. It is clear that long segment lengths have only a trivial

discrepancy in time estimation but short segment lengths incur non-ignorable differences. This gets more severe in the case of higher feed speed conditions. When the segment length is longer than 10mm in Figure 4.11, the estimation error is trivial in most feed speed conditions, a few percent. On the other hand, when the length is shorter than 5mm, the influence of the feed speed on the estimation error gets larger. For a 2mm segment length, the estimation error is 5% at 500mm/min feed but the value increases to 70% at 2000mm/min feed speed. This implies that the tool paths with many short segments need more consideration in using nominal feed speed as an analysis parameter or substantial errors will result.

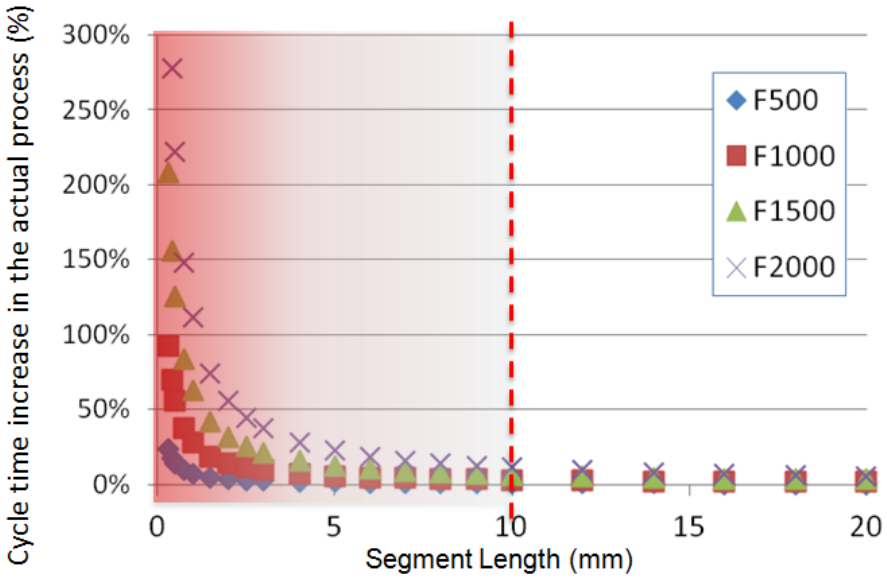


Figure 4.11. Temporal deviation according to tool path segment length

4.7 Structural Configuration of a Machine Tool and Direction of Axes Movement

A machine tool is made of many different functional components. Generally, a machine tool structure is designed to be heavy to provide sufficient stiffness which minimizes vibration and achieves more accuracy in high speed machining. This heavy structure tends to waste energy in moving the structure. Hence, to reduce the waste, various strategies like downsizing [66] and dematerialized machine tool design [67] were proposed.

This structural configuration affects the energy consumption characteristics of a machine tool. In the multi-axis machine tool, cutting tool and workpiece table are driven by a number of motor actuators. Each axis movement is independent of the other. Assuming the same motor actuator efficiency for all the axes, the energy to drive an axis is simply proportional to the mass loaded on it. For conventional vertical machining centers, the X-axis is usually placed on the Y-axis resulting in more mass loaded on the Y-axis. This discrepancy in the power requirement for each axis can be resolved by placing actuators of different power ratings dependent on the load

or of a different number. For example, when the load to the Y-axis is twice of that to the X-axis, machine tool designers may place two motors on the Y-axis and one motor on the X-axis to make a more efficient design.

Because of these structural considerations, understanding the different power demand on each axis is needed to predict the energy consumption of the machine tool. Figure 4.12 shows experimental results with a Mori Seiki NVD 1500 vertical milling machine. In this figure, the power demand of jogging shows a clear difference between X- and Y-direction movement [57]. According to this chart, more power is demanded by movement to Y-axis than to X-axis. While this power demand includes those of the other components, higher power demand on the Y-axis gets more apparent with higher feed rate.

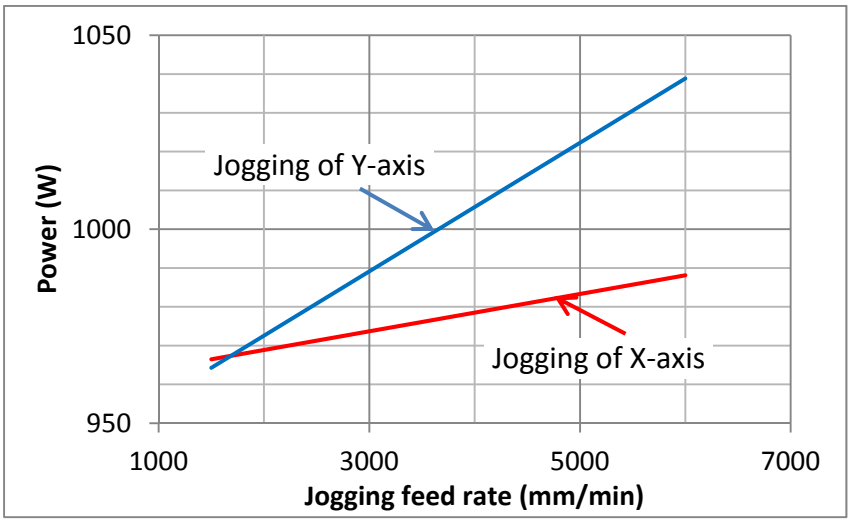


Figure 4.12. Different power demand of jogging the Mori Seiki NVD 1500 milling machine

On the other hand, movement with concurrent actuation of two or more axes can attain higher maximum speed as shown in Figure 4.13. This calculation is based on the vector addition of the components to two axes. The maximum feed rate in the X- and Y-directions can be assumed to be the same. In this case, assuming maximum feed to each axis, combined available feed speed is larger than that of one specific axis. Hence, the maximum feed rate in the X-Y plane is achieved at the 45 degree orientation when each axis performs at the same maximum value.

This implies that there exists an optimal direction at which feed rate can be maximized and thereby reduce the cycle time and energy consumption. This result is consistent with the work of Rangarajan et al. [62], who showed that the direction of cutting tool movement in two axes strongly influences the processing time. This also implies differences in capacity of acceleration and deceleration according to the movement direction. Because acceleration/deceleration is performed with the largest tangent acceleration/deceleration not exceeding the acceleration set for each axis, acceleration capacity is different in each direction. This different capacity may

affect related feed profiles and as a result, actual feed speed. Hence, orientation of tool path segments must be considered to predict actual feed speed.

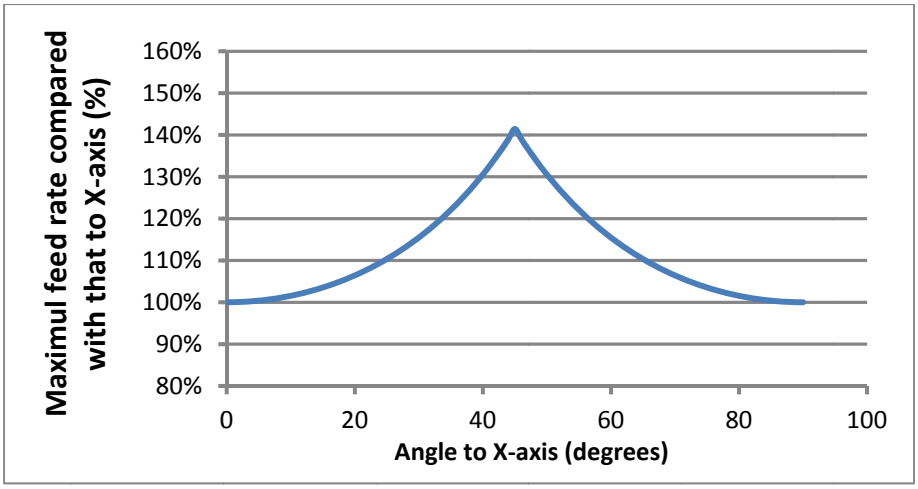


Figure 4.13. Maximum feed rate and direction of cutting tool movement.

4.8 Tare energy and cycle time prediction

As explained in the previous sections, the proportion of tare energy is dominant in the total power demand of a CNC milling machine tool. In Figure 4.14, the power demand distribution of a Mori Seiki NVD 1500 CNC milling machine is described [66]. Components directly related to the machining are cutting, coolant pump, spindle rotation, and table feed. However, power demand of these components is less than 40% of total power demand.

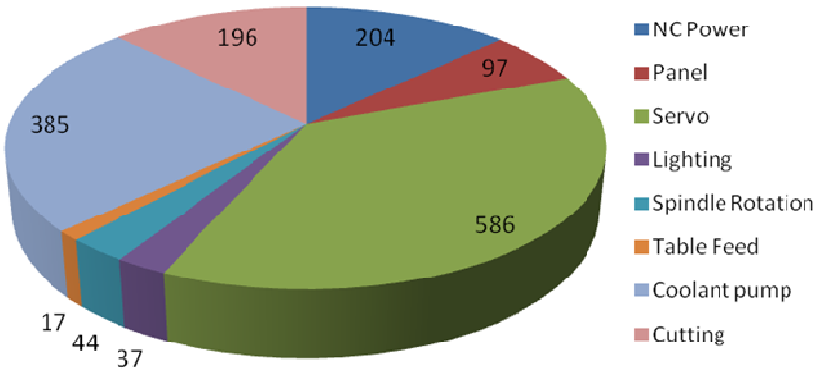


Figure 4.14. Power consumption distribution of Mori Seiki NVD1500 [66]

On the other hand, operational efficiency in the manufacturing sector is not high. According to a white paper from ABB, Overall Equipment Efficiency (OEE) of top level manufactures is about 85% and more generally, 60% [68]. OEE, which is defined with equation (4.23) below, is a way of measuring the effectiveness of a machine. Hence, this low value indicates that a large portion of time is wasted without producing any value. However, even in this non-productive time, significant energy is wasted due to the fixed energy consumption of a machine.

$$\text{OEE} = \text{Availability} \times \text{Performance} \times \text{Quality factor} = \frac{\text{Valuable operation time}}{\text{Theoretical production time}} \tag{4.23}$$

Considering this low efficiency and high tare energy consumption for a corresponding time span, appropriate cycle time management is important to enable more energy efficient process planning. At the machine level, designing a machine which minimizes energy waste with optimized components management would be needed as Schmitt et al. suggested [69]. At the process level, to minimize fixed energy consumption, an appropriate process plan is necessary which maximizes the process rate and minimizes the non-productive time [47]. For this, reliable cycle time estimation is necessary. Based on this, effective process planning including scheduling turn off cycle for machine tools, can be designed. Currently, due to poor accuracy of the cycle time data, safety factors are applied for the process plan and this further increases the non-productive time. Appropriate cycle time estimation is more important in many automated facilities where the tare energy makes a greater proportion of the power demand breakdown of the machine tools.

4.9 Impact of Geographical Region on the Green House Gas Emission

Along with the characteristics of machine tools mentioned in the previous sections, geographic location also affects the GHG emissions associated with electricity consumption [70]. Electricity consumption in the use phase is the most influential part related to environmental impact of machine tools.

However, as described in Figure 1.2, different fuels are used for electricity production at different locations and this causes different emission characteristics. Table 4.2 shows the GHG emissions for electricity production with different resources [71]. According to this table, while there is almost no environmental impact related with electricity produced with hydropower, a significant amount of GHG is associated with that produced with fossil fules such as coal.

Because GHG emissions vary according to the sources of electricity and each geographic region has a unique dependence on fossil fuels for electricity production, GHG emitted as a result of electricity use by a machine tool to execute a tool path also varies geographically.

Table 4.2. GHG emissions from electricity production with different source [71]

Values (g CO2/kWh)		Minimum	25th percentile	50th percentile	75th percentile	Maximum
Biopower		-633	360	18	37	75
Solar	PV	5	29	46	80	217
	CSP	7	14	22	32	89
Geothermal Energy		6	20	45	57	79
Hydropower		0	3	4	7	43
Ocean Energy		2	6	8	9	23
Wind Energy		2	8	12	20	81
Nuclear Energy		1	8	16	45	220
Natural Gas		290	422	469	548	930
Oil		510	722	840	907	1170
Coal		675	877	1001	1130	1689

(CCS = Carbon capture and storage, PV = Photovoltaic, CSP = Concentrating solar power.)

Table 4.3. Green house gas emission rates for electricity generation by states.

Values (Lb/MWH)	**NO_x**	**SO_2**	**CO_2**	**CH_4**	**N_2O**
CA	0.2231	0.1358	540.06	30.60	4.50
NY	0.8867	2.4531	828.33	36.96	10.41

To evaluate the influence of the geographically different energy mix (shown in Figure 4.15) on the GHG emission during electricity generation, data obtained from U.S. Environmental Protection Agency (EPA) was used [72]. Table 4.3 shows different GHG emission rates associated with the electricity generation in California (CA) and New York (NY) based on this data. This difference results from the fact that while CA depends on natural gas and renewable energy in large portion, NY depends more on coal as seen in Figure 4.15.

This geographical influence on the GHG emission also holds true at a global scale as long as the energy mix varies. Figure 4.16 shows the energy mix of several European countries for electricity generation. Similar to the previous example comparing CA and NY, the GHG emissions from electricity generation in France are very different from that in other countries. This is due to much lower dependency on fossil fuels and higher dependency on nuclear energy in France. As a trading barriers between different countries and supply chains get more complex and global scale, millions of tons of CO2 are traded in various ways by the distributing manufactured products [73]. Hence, energy mix information also needs to be considered at a large scale.

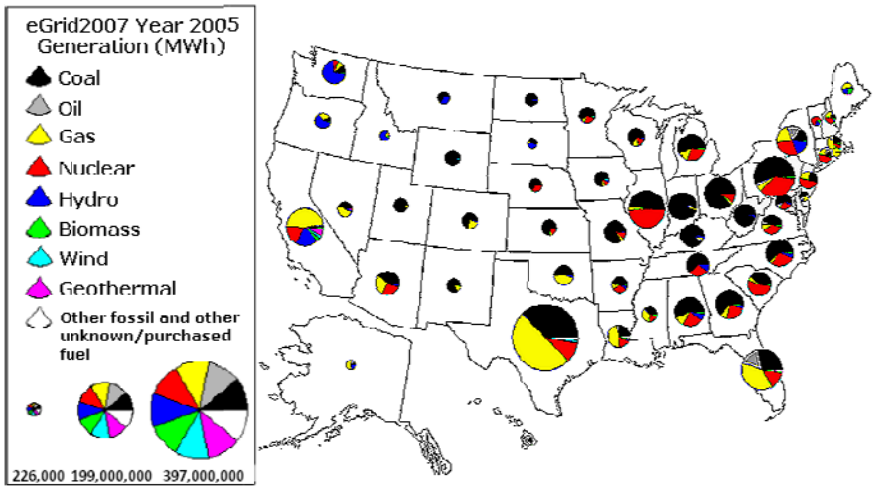


Figure 4.15. Energy mix in the USA from U.S. EIA 08 [7]

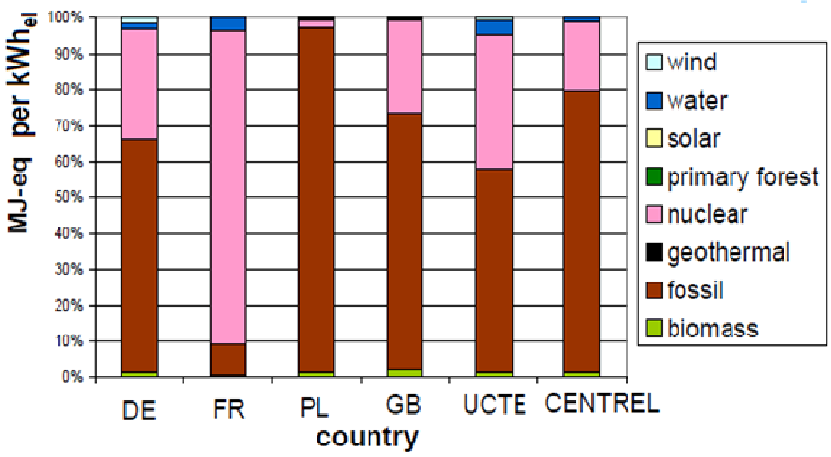


Figure 4.16. Energy mix of several countries for electricity generation [74]

4.10 Experimental Validation

Milling operations and electrical consumption measurements were carried out to assess the process characteristics of the CNC milling machine tool. Figure 4.17 shows the power meter (Yokogawa CW240) connection to the milling machine (Mori Seiki NVD1500). Three phases and a ground connector were clamped to the power unit of the machine tool as shown in the figure. Through the power meter, real time information of current, voltage, and power was assessed through the experiment. Higher frequency of 60 Hertz is available with the power meter but the measured data with this frequency is hard to analyze due to noise in signal. Hence the sampling frequency for data was set to 10 Hertz during experiments. An aluminum based 76mm by 76mm rectangular workpiece was used for machining. Assessed information was converted to an Excel sheet and analyzed.

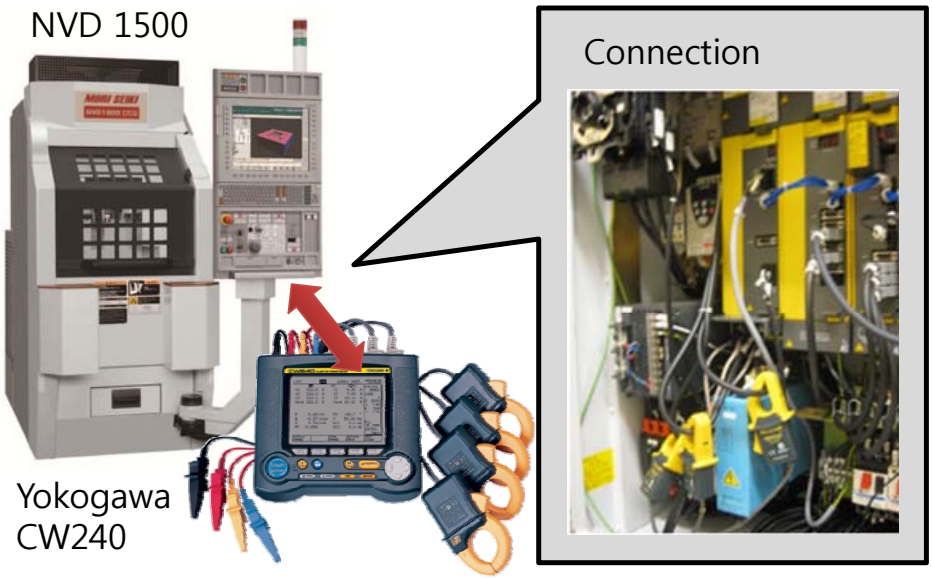


Figure 4.17. Power meter (CW240) connection to NVD 1500

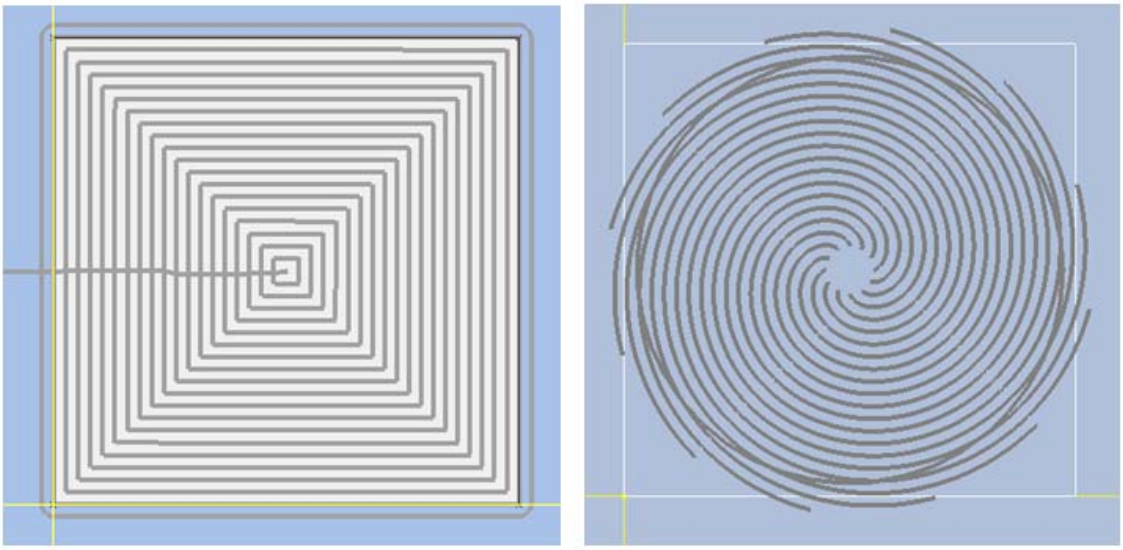


Figure 4.18. Rectangular pocket and curved profile tool paths

Two tool paths were designed for those experiments: one composed of rectangular profiles with different lengths and the other composed of smooth curves defined as involutes of a circle, Figure 4.18. As the tool moves to the inner rectangle, the cutting tool is fully engaged with the workpiece and removes a short slot. This helps to distinguish rectangles of different lengths more easily. Involutes of a circle can be understood as the trace of the thread end of a line which is spooled from a circular pulley. The curve is expressed by the following equations for the X and Y coordinate space:

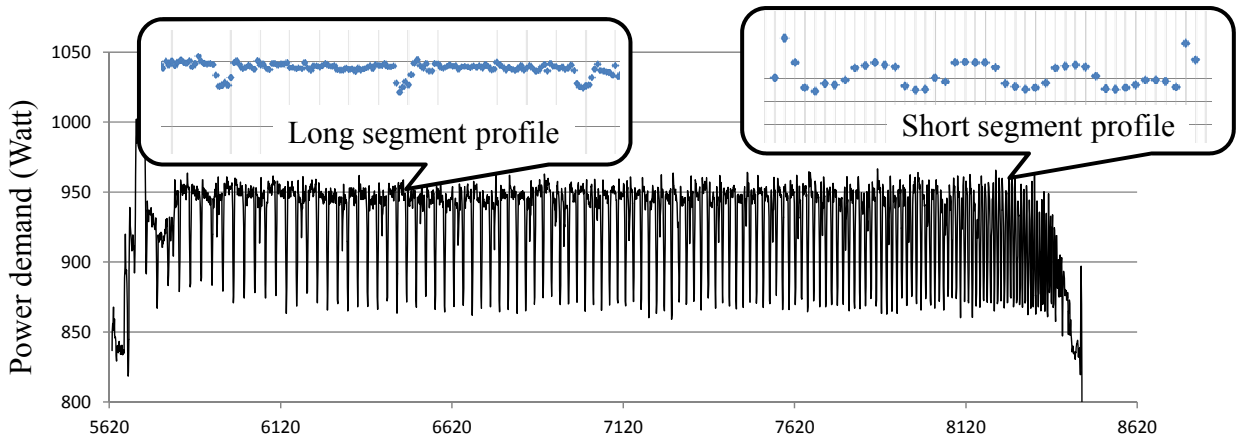
$$x = r_i \times (\cos t + t \times \sin t) \quad (4.24)$$

$$y = r_i \times (\sin t - t \times \cos t) \quad (4.25)$$

where r_i is the radius of the circle and the variable t is an angular deviation in radians from the initial position. The radius of curvature of this curve increases with radial distance from the center. The step size between two adjacent curves is kept the same. Hence, one can check if the small curvature influences the milling operation. Each curve is connected with a rapid traverse tool motion, which is known to demand high power.

4.10.1 Rectangular pocket tool path

Figure 4.19 shows the power profile during the machining of rectangular pocket. The X-axis of the chart is the time measured in 1/10 second units. The Y-axis is the power measured by Watts. As expected from the previous sections, the power profile shows apparent transitions of the up and down pattern at the start and end point of all the line segments. As the tool path segment length decreases, the peak power range also decreases. According to the experimental results under different load conditions, transition points are not affected by the load but power demand increases in proportion to the load.



Tool	Φ8mm end mill	Material	Aluminum
Width of cut	2.0 mm	Feed	1500mm/min
Depth of cut	2.0 mm	Spindle	10000rpm

Figure 4.19. Power profile and machining for rectangular pocket milling

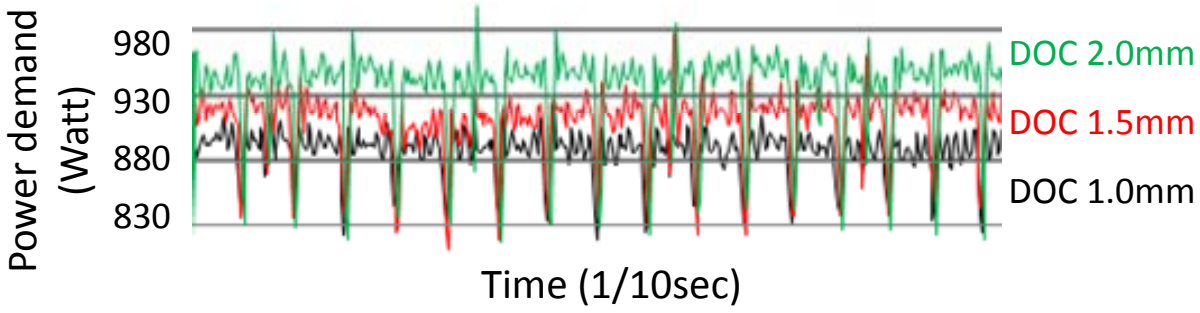
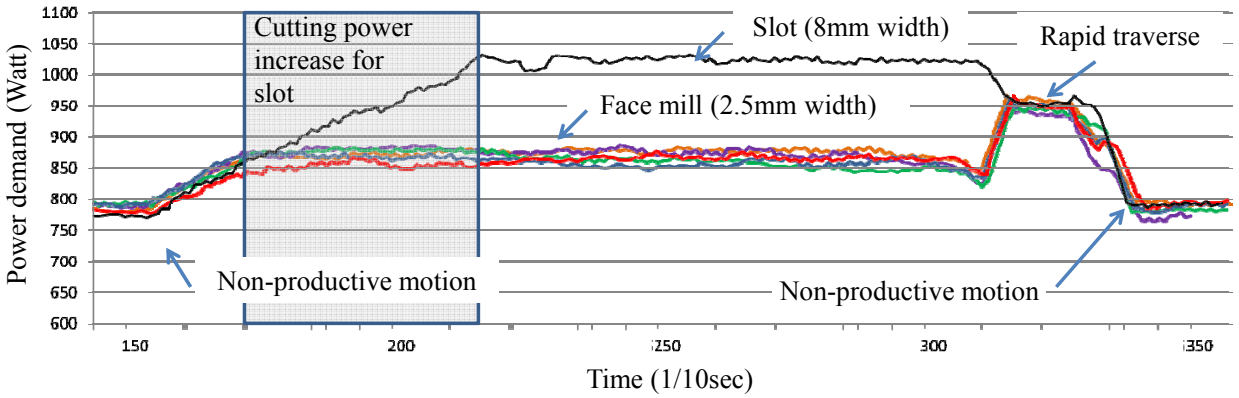


Figure 4.20. Power profile with different load conditions

In Figure 4.20, three different depths of cut were compared. Peak power demand at each condition was measured to be 960W for the 2mm depth of cut, 930W for the 1.5mm depth of cut, and 900W for the 1mm depth of cut. The lowest value of the profile is 830W for all different load conditions. The lowest point occurs when the tool feed is zero and only the tare power demand is consumed. According to this experimental result, it can be assured that while the power demand from the table feed is not so large, the feed controls the power profile.

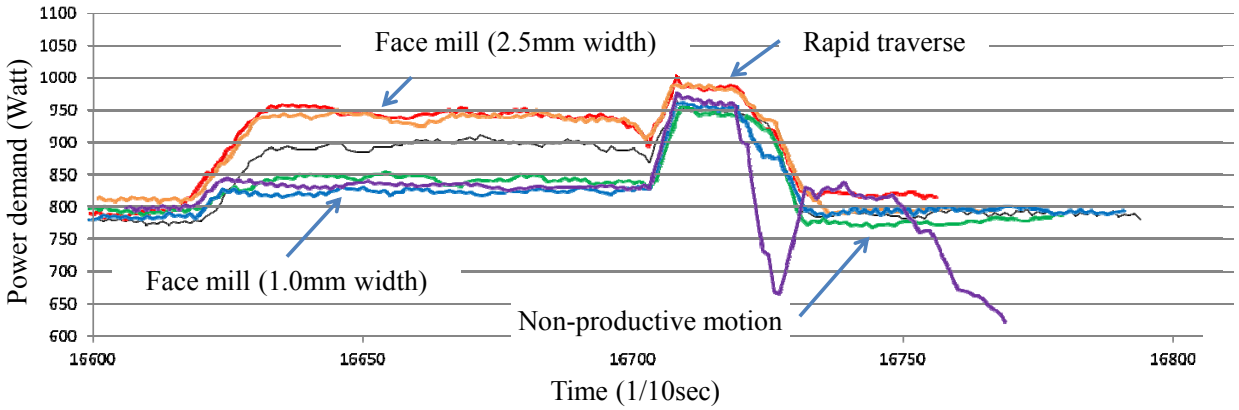
4.10.2 Curved profiles

Figure 4.21 shows the power profiles during the machining of the curve tool paths. As explained in section 4.6, smooth tool paths follow the feed profile of Figure 4.10. Because tool paths are smoothly connected, there is no clear transition point which occurs frequently in the rectangular pocket machining of Figure 4.19. All the profiles almost overlap each other. This implies that the actual cycle time for each path is almost the same. However, as expressed in both graphs, the upper bound of power demand varies with load condition. Looking at the boxed part in Figure 4.21, while all the profiles show the same slopes, the black line ascends longer resulting in higher power. This profile is for the first pass which produces the slot at higher load. Considering the same cycle time for each case, the difference seems to be the result of the spindle load which is not covered in this research. The value of the high cutting power is 1030W and the low cutting power is 870W. As shown in the graph, power demand during idling mode is 800W. Considering the width of cut of 2.5mm and the tool diameter of 8mm, this power demand discrepancy is directly proportional to the depth of cut.



Tool	Φ8mm end mill	Material	Aluminum
Width of cut	2.5 mm	Feed	800mm/min
Depth of cut	2.0 mm	Spindle	10000rpm

Figure 4.21. Power profile of curves profile milling with 800mm/min feed rate



Tool	Φ8mm end mill	Material	Aluminum
Width of cut	2.5 mm	Feed	1500mm/min
Depth of cut	2.0 mm	Spindle	10000rpm

Figure 4.22. Power profile of curves profile milling with 1500mm/min feed rate

The peak power region on the right side shows power demand for the rapid traversal mode. Except the case of initial slot cutting, rapid traversal shows higher power demand than cutting. Comparing the power demand of the cutting paths and the non-productive paths, this experiment shows that only 61% of the energy is consumed for machining and 39% of the energy for non-productive paths under the 800mm/min feed condition. It is worse for the 1500mm/min condition shown in Figure 4.22, where only 45% of energy is consumed for machining. This result supports the need to consider power demand in rapid traverse as an important part in energy consumption analysis in milling operations.

4.10.3 Influence of the segment length

Figure 4.23 shows the discrepancy between the actual and ideal cycle time for the two different path types in Figure 4.18. A large discrepancy is found for the short length range in both cases. As expected, this is more distinct in the case of the rectangular pocket in which all the tool segments change direction perpendicularly. In the curved tool paths in which all the segments are smoothly connected, a large discrepancy is found only at the very short segments shorter than 0.3mm. This shows the advantage of high speed milling. However, when these paths are applied to small precision molds and dies, which are commonly used in the production of various electronic products, even the curved tool paths can be affected by this discrepancy.

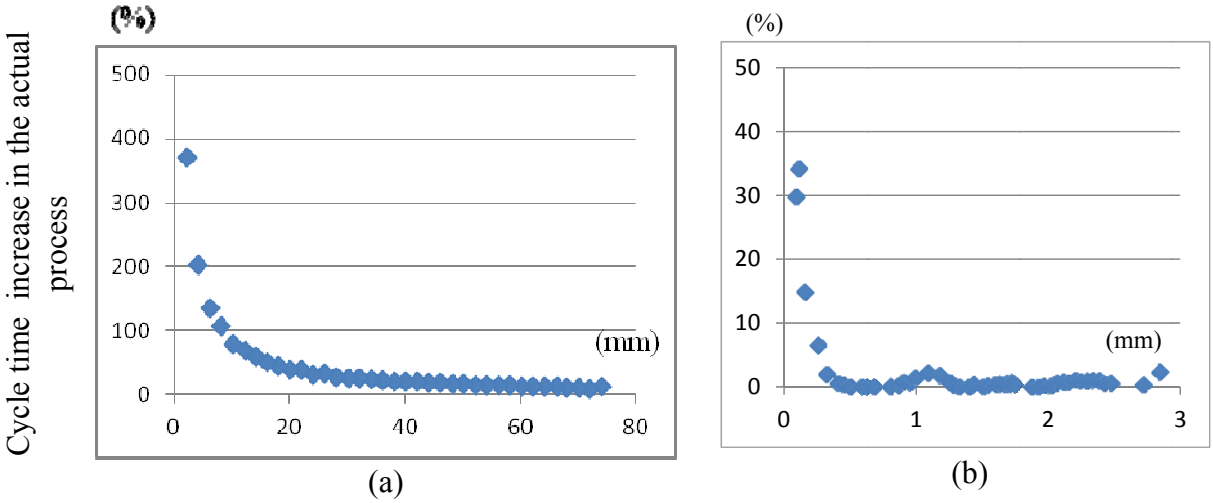


Figure 4.23. Discrepancy rate of actual cycle time to ideal time in (a) a rectangular pocket tool paths and in (b) a curved profile.

4.11 Milling process and software simulation

Figure 4.24 shows the process flow of tool-path planning for the milling operations discussed in this thesis. Two verification steps (data analysis for manufacturability and tool path evaluation for productivity and accuracy) are generally used in traditional processes. Sustainability assessment as a new measure can be added to the tool path evaluation step.

When target design data for a product or component arrives, CAM engineers check the design data for manufacturability before developing a machining strategy to see if the design has any problems. Generally, engineers create a tool path based on their experience, and this tool path data is transferred to a machine operator for machining. When the factory is relatively large, a process planner plans the manufacturing process and assigns available machines for the execution of the tool path.

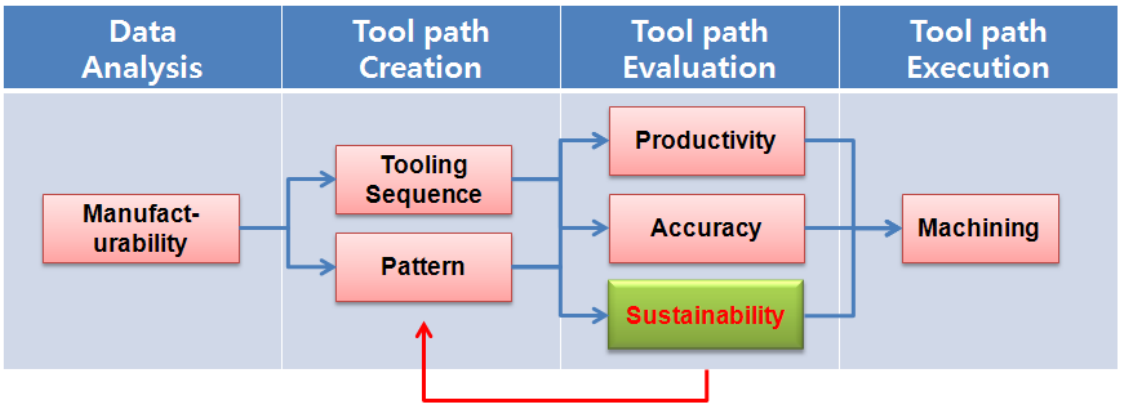


Figure 4.24. Process flow for tool path planning incorporating a sustainability concern

Because of the complexity and the difficulty in tool path evaluation, manufacturing engineers utilize various simulation software tools. The main objective of these is to minimize expected problems in machining including undercut, overcut, rapid motion contact, and collisions between the cutting tool and fixture or workpiece. These problems are checked by graphical simulation and geometric computation within a selected accuracy level.

Traditional simulation has been principally concerned with product quality and productivity, while the sustainability and energy efficiency of a tool path has not yet been addressed. Moreover, the intangibility of the environmental impact-related aspects of a tool path has made it difficult to include in the tool path planning process. Nevertheless, improving simulation coverage by incorporating impact or sustainability concerns is required to comply with the increasing demand for sustainable product development and environmental impact reduction of machining processes.

4.12 Modeling

To measure impact of machine tool use, a relevant model that explains the energy consumption behavior of the machine tool is required. Specifically, a model that estimates the energy consumption and GHG emission resulted from material removal behavior was developed. Figure 4.25 shows the basic structure of the model.

The model takes NC code that controls the motion of a machine tool, machining parameters including the cutting tool list and the specification of a machine tool and geographical information that reflects the energy mix of the electricity. The inputs are then processed to evaluate the time required to execute the NC code and the GHG emissions resulting from the material removal behavior of the machine tool to run the NC code, which represents the performance and the sustainability impact of the machine tool operation, respectively. The life cycles of the cutting fluid and cutting tool also have an impact on the environment through the product being machined but were not considered here for simplicity of the analysis. Instead, these factors can be estimated as a multiple of the evaluated process time [25] [75].

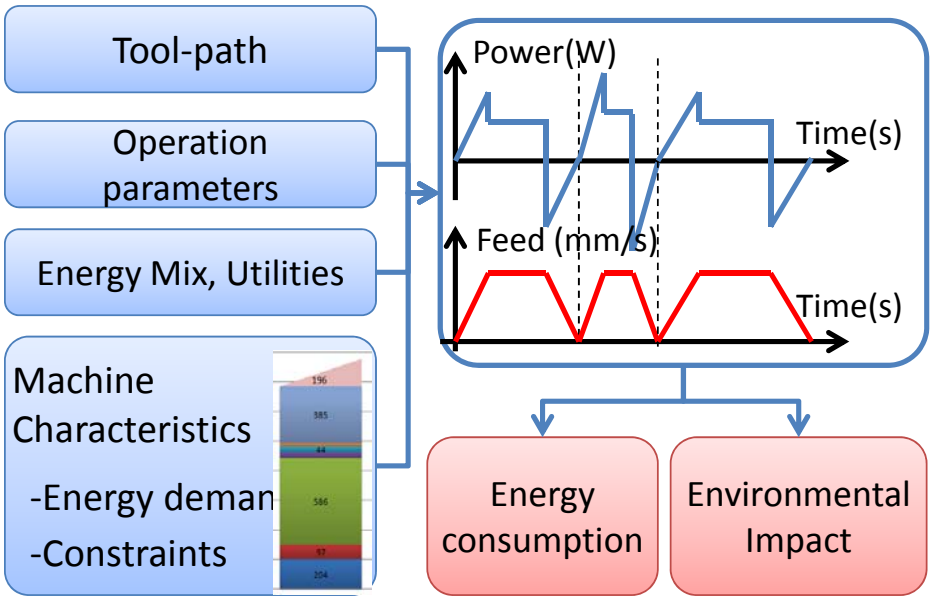


Figure 4.25. Architecture of the simulation software

4.13 Implementation

Two tool path evaluation tools, both incorporating a measure of the energy consumption and resulting GHG impact, were implemented: one is the web-based service software where a central database is used and the other is the customized CAM software tool. These applications or a combination of both can be used in manufacturing.

4.13.1 Web-based Software Implementation

In the web-based program, a central database system contains standard information about related machine tool operation and evaluation logic for cycle time, energy consumption and GHG emission. Since all software resources are concentrated at the central database and shared over the network, any changes in this system will directly be reflected to other connected processes. This increases consistency over the system but requires careful management of rules and information. Figure 4.26 shows the structure of this system.

Evaluation logic and a GUI were implemented in the web server with a PHP (Personal Hypertext Preprocessor). Information about the machine tool and geographical energy mix data are stored in the database. A planar face was assumed for raw material geometry. When users open a web-page and input an NC (Numerical Control) code containing tool paths, cutting tool list, a machine tool that would run the code and the geographic information on the machine tool location, the cycle time, the energy consumption and the GHG emission for executing the NC code will be estimated by pre-defined evaluation logic.

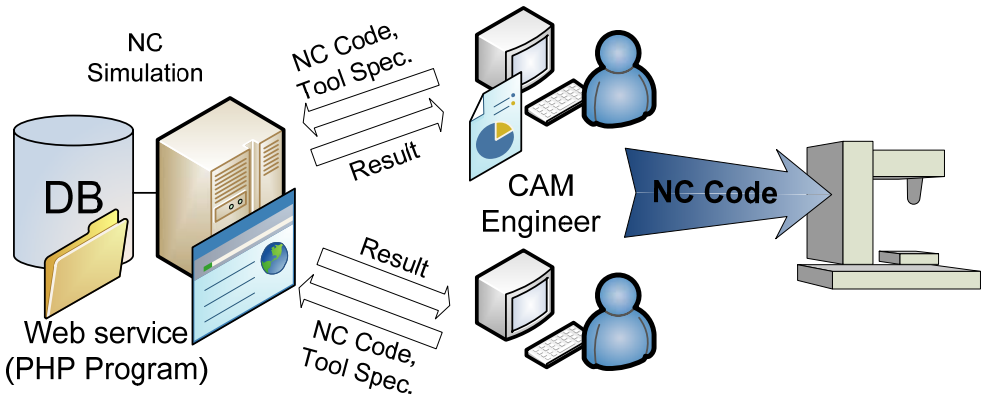


Figure 4.26. Web-based simulation environment

The candidate NC code is parsed block-by-block sequentially with only those blocks that cause either an actual motion of the axes (e.g., G00/1/2/3/28/81) or imply tool movement as a result of some other function (e.g., M06). During the parsing process, the software tracks the tool tip position, current active command, and current feed to enable efficient calculations of energy and time.

When calculating the processing time, the time to execute a single block of NC code was first calculated by summing the time required for accelerating (at the beginning of a block), decelerating (at the end of the block) and moving the axis at the commanded feed rate. Non-motion times, such as the time required for tool changes, were also considered when calculating the total processing time.

4.13.2 API-based Software Implementation

Most of commercial CAM software providers supply application programming interface (API) in their solutions to allow customization. Esprit CAM™ software and its API was used in this thesis to implement functions. The same information about a machine tool and geographical energy mixes that were used for the web-based software were used but stored as component files of each application in a personal computer. This structure of the software is shown in Figure 4.27.

Since every CAM software tool has a distinct API, API applications need to be customized when used for different CAM software while maintaining the basic logic and database. This increases the burden of maintaining the consistency in rules and information among various CAM software or computers. On the other hand, users can implement more complex and powerful functions with the help of the API. Besides, compared to the web-based program for which tool-path planning and evaluation of sustainability of a tool path (i.e., energy consumption and GHG emission) are separated, an API-based program allows users to implement integrated software.

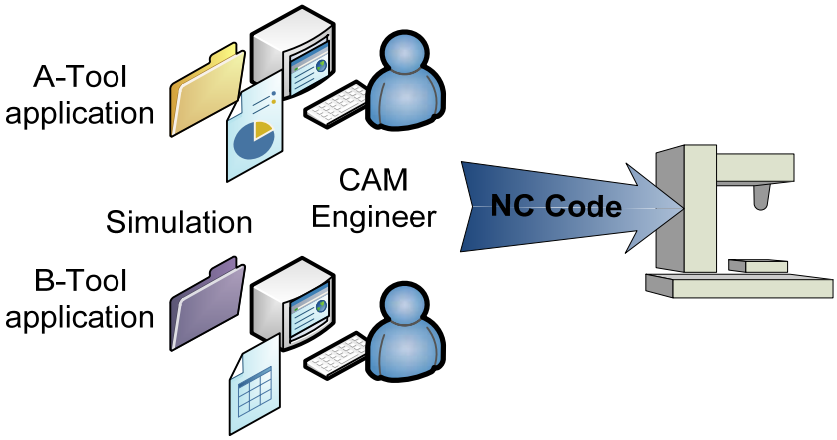


Figure 4.27. API-based simulation environment

API-based software requires users to select a candidate tool path strategy from a list instead of loading an NC code that was generated from other CAM software. The variables in a tool path such as feed rates, spindle rotational speed and depth or width of cut can be adjusted and the cycle time, the energy consumption and the GHG emission can accordingly be evaluated in the API implemented software by using the information on the machine tool and geographical location. These evaluated data are compared by changing the variables in a tool path and the data will be written in the format of Excel sheet containing tabulated output values and a chart comparing the output.

4.14 Test Cases

Two different examples were compared to explain the influence of tool path strategy on the cycle time and environmental impact of the milling process.

4.14.1 Rectangular pocket milling with different tool path patterns

This analysis utilized the structural configuration of a Mori Seiki NV 1500. In this machine the y-axis has two drive motors while the x-axis has one since it sits on top of the y-axis. Energy consumption for the z-axis was assumed to be the same as that of the x-axis, which ignores the effect of gravity on the energy consumption of z-axis.

A rectangular pocket (100 mm wide, 100 mm high and 40 mm deep) was chosen as a target design and five different tool path strategies were compared using the evaluation tool. The outermost box shows the edges of the pocket and the curves in the box show the tool paths. A 20mm diameter flat end mill was used for the rough cutting and a 10mm diameter flat end mill was selected for the finishing. The feed rate for both tools was 500 mm/min for movement in x- and y-direction and 100 mm/min for movement in z-direction. The spindle speed was 2000 rpm

for rough cutting and 5000 rpm for finishing. The amount of overlap between tool paths was kept constant at 35% and the depth of cut was 10 mm for rough cutting.

The cycle time and energy consumption were calculated for each tool path. Figure 4.28 shows that longer tool paths generally require longer processing time (cases (d) and (e)). The energy demand is also proportional to the processing time with the exception of case (d).

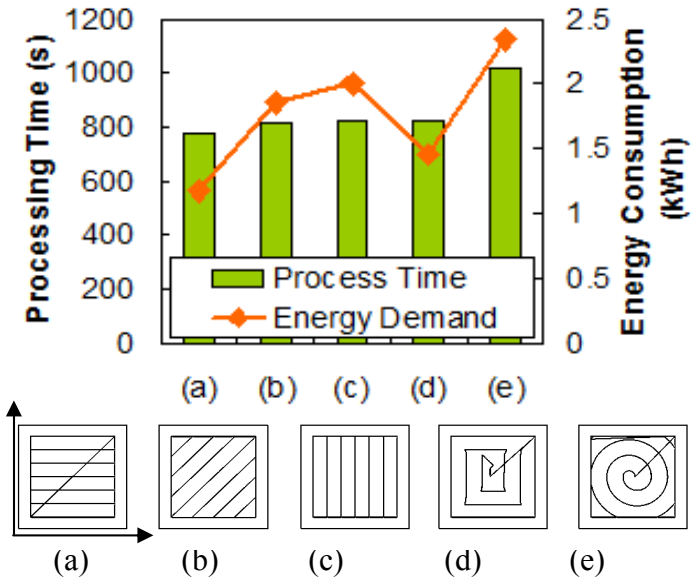


Figure 4.28. Processing time and energy consumption of various tool-paths

Case (d) shows the influence of the moving direction of the tool path on the energy demand. Moving principally in the y-direction requires more energy due to the design of the Mori Seiki NV1500 – more mass is in motion since the x-axis is carried by the y-axis and two drive motors are utilized versus only one for the x-axis. This influence is more evident when comparing cases (a), (c) and (d). The tool path in case (a) is mostly in the x-direction, while case (c) is in the y-direction and case (d) is balanced between the two directions. These different characteristics make the energy demand of case (c) the highest among the three followed by case (d) and (a). Also, the energy demand for case (b), which is between those of cases (a) and (c), reflects the balanced movement of both the x- and y-axes.

GHG emissions associated with the operation of the tool path in Figure 4.28 (a) are compared across five common manufacturing states in U.S. Figure 4.29 (a) shows the total amount of GHG emission and dominant contribution of carbon dioxide.

Figure 4.29 (b) shows the other GHGs except carbon dioxide that are not evident in Figure 4.29 (a). The proportion and total amount of GHG emissions reflect the energy mix in Figure 4.15. For example, when the machine tool is operated in Indiana where electricity is mostly

generated by coal, the amount of GHG emission is nearly four times of that in California where gas, nuclear and hydro are the main sources of the electricity.

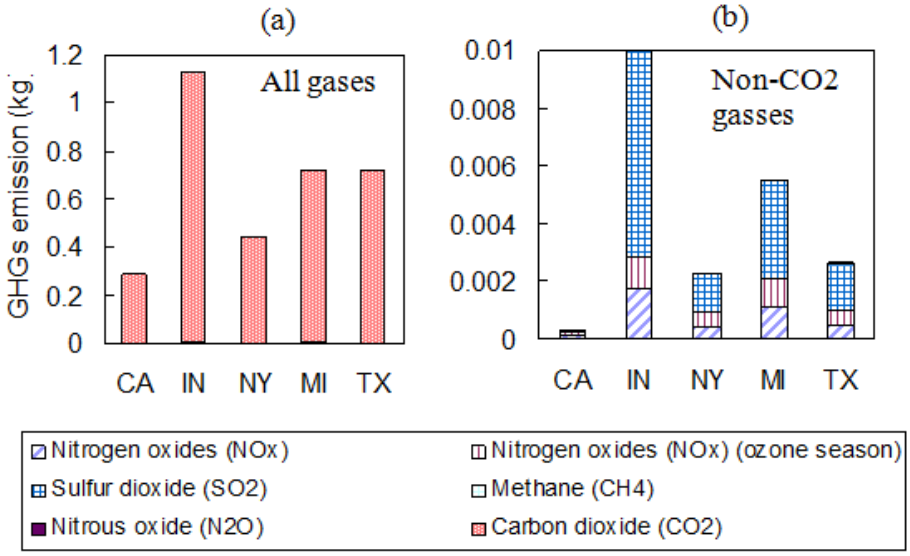


Figure 4.29. GHG emissions resulted from executing a sample tool path in five arbitrarily chosen states (Figure 4.29 (a) shows all the GHG emissions and Figure 4.29 (b) shows the GHGs except carbon dioxide.)

4.14.2 Various surface shapes with different tool path patterns

Five different tool paths were compared in terms of cycle time in Figure 4.29. Each tool path has a different composition of tool path segment lengths. Facing is using zigzag paths composed of long segments and a small pocket is spiral paths with relatively short segments. For three different feed speeds, actual operation time and a nominal time were compared for each tool paths. As shown in the figure, almost no discrepancy exists in case of facing tool paths. On the other hand, the actual time for the small pocket dramatically increases the discrepancy with feed speed increase. The other tool paths show small increases in discrepancies. This example shows how tool path composition affects the cycle time in the milling process. If possible, longer segments are preferred from the cycle time perspective.

SolidMill Trochoidal pocketing was chosen as the test strategy to machine the curved pocket shape shown in Figure 4.30. Seven different feed rates from 500~1000 mm/min were tested as variables and Indiana (In) was arbitrarily chosen as the geographic location of the machine tool. The rotational speed of the spindle was maintained as constant to 2000 rpm and 50% of overlap between tool paths was used.

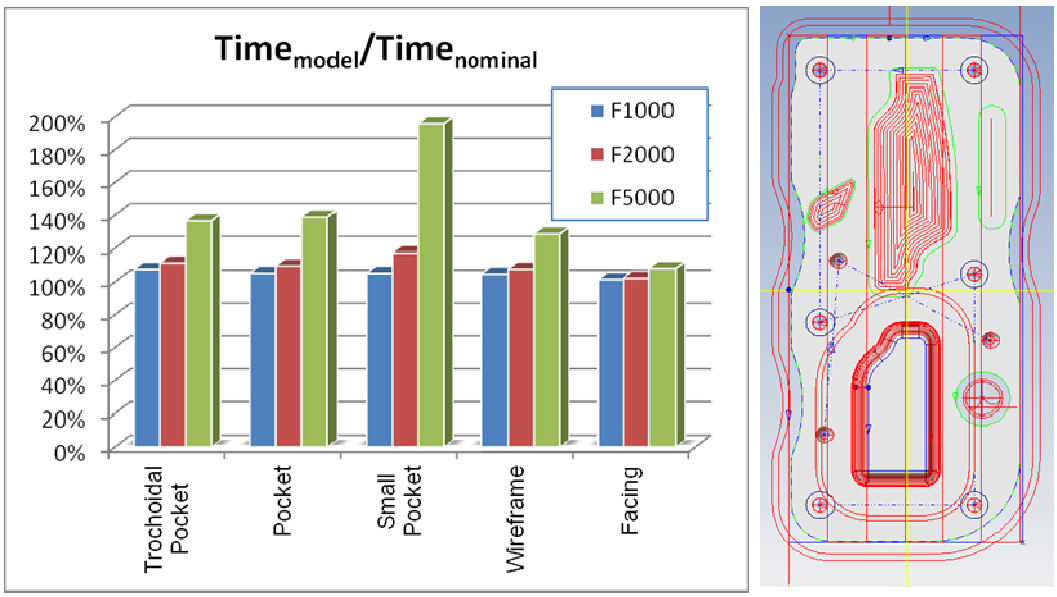


Figure 4.30. Tool path influence on the cycle time variation

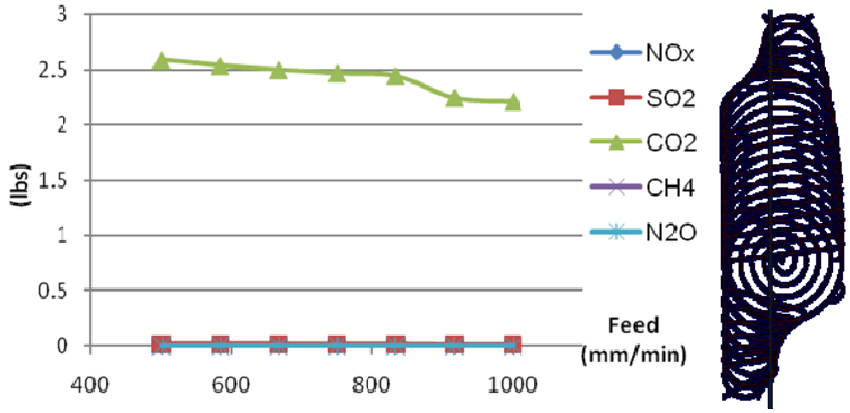


Figure 4.31. Green house gas emission as a result of electricity consumption for machining a pocket shown in the left in Indiana

GHG emission during the pocket machining assuming machining was done in Indiana was evaluated as shown in Figure 4.31. It shows that CO_2 is the dominant GHG for all the cases and the other GHGs are not evident in the figure due to small amount of emissions. It also shows that GHG emissions are not linearly proportional to feed rates. This is a consequence of the additional energy demanded for acceleration or deceleration and the discrepant axis characteristic of a machine tool.

4.15 Conclusion

Two analysis software tools were implemented and tested for the type of milling operations used extensively in die and mold making.. Analysis showed that the patterns of the tool path influence the amount of energy required to machine the part. Also, varying the location where the machining is conducted resulted in a different amount of GHGs associated with the machining. These findings suggest that better decisions can be made by considering both performance and environmental impact when machining process planning.

Actual cycle time and energy consumption are always more than estimated in the ideal situation. On this issue, it was found that the feed profile for each axis and the machine structure affect the actual performance of the CNC milling process. Related to this, short tool path segments were found to involve much longer cycle time than planned and decrease the actual operation performance. These factors were included in the analysis to improve the reliability of the analysis data.

The limitations of MRR-based analysis methods were discussed. Due to the high portion of non-productive time and large tare energy of most machine tools, energy consumption during the non-productive time cannot be ignored. Furthermore, the high power demand of rapid traverse motion also emphasizes the limitations of MRR-based methods. With a tool-path based analysis, this limitation is now addressed in this thesis.

Table 4.4. Comparison of two implementation approaches.

	Web-based	API-based
Control	Easy	Difficult
Functionality	Small	Large
New Technology	Late	Fast
Tool dependency	Low	High

Comparison of the web-based and the API-based approaches are listed in Table 4.4. The table shows that web-based tools are easier to control and less dependent on the software tools in which they are implemented than API-based tools. As a result, the web-based approach gives users more freedom of control. However, the API-based approach can provide more benefits based on the various functionalities of the tool where it is implemented. Thus more complex functions can be implemented with less effort than with the web-based approach. For the same reason, new technologies can be easily updated in the API-based application through the software tools in which it is implemented.

The approaches presented in this work are applicable to a wide range of applications where sustainability analysis is desired. Hence, these approaches can be used to evaluate more specific environmental concerns in product development and to complement existing LCA tools which provide comprehensive information.

Chapter 5

Environmental impact of Electric discharge machining

5.1 Introduction

Electrical discharge machining (EDM) is perhaps the most popular and effective non-conventional machining process. Since its introduction in the 1960's, EDM has expanded its usage over various material removal processes with the development and application of CNC, adaptive control and high speed servo technologies. EDM is a typical non-contact electro erosive machining process which has gap between the tool (electrode) and work-piece. Work-piece material is removed by thermal energy of the spark between the electrode and work-piece immersed in dielectric fluid. This enables EDM to overcome the other physical contact-based machining processes' limitations like vibration and tool forces. Difficult shapes like deep slender holes or ribs can be easily machined. Hardened materials like titanium and steel alloy also can be easily handled with EDM. This capability gives EDM the current popularity in the machining industry.

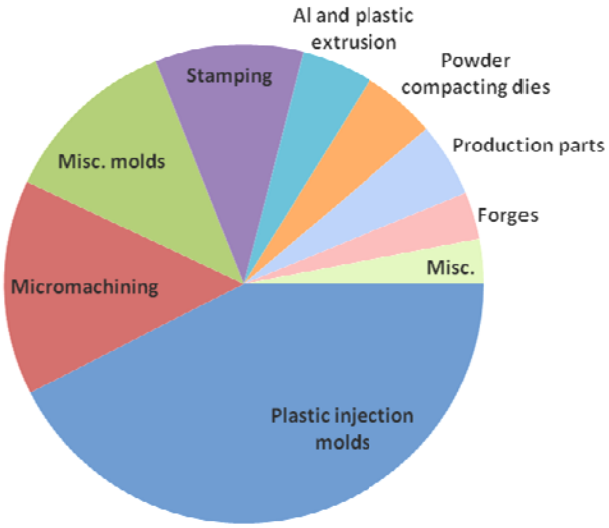


Figure 5.1. Die sinking EDM usage by applications [35]

Mold and die manufacturing is the biggest consumer of EDM technology. According to a report, almost 80% of die-sinking EDM applications are related to molds or dies [35]. In the following chart, Figure 5.1, except for micromachining and production parts, all other parts are types of molds or dies. With improvement in product development technology, more difficult to machine shapes are required and hard material is preferred to produce more products in large

quantities with one mold or die and reduced maintenance requirements. These preferences explain why EDM has become an indispensible process in mold and die making. Actually, in many cases, EDM is found to be the only possible way to address various needs in mold and die manufacturing and has allowed higher complexity in design.

The machining efficiency of EDM is much lower than that of other processes and EDM generally takes a long time for machining. Nevertheless, due to the needs for high quality in precision molds and dies and the hard material requirements, EDM has become the 4th largest selling machine tool following milling machines, lathes, and grinding machines [76]. With respect to operation time, EDM is claimed to be the second most time-consuming process next to milling in mold and die manufacturing [36]. Therefore, an appropriate analysis of EDM is indispensible for mold and die manufacturing.

In this chapter, EDM will be explained in detail for mold and die manufacturing. Operating characteristics of EDM will be covered and the energy consumption of the machine will be explained. Based on a literature review, an EDM operation model will be proposed in terms of MRR. Process performance and related energy consumption will be estimated using this model. Experimental results also will be described to support and validate the model.

5.2 Basic theory of EDM

The principle of EDM is quite straightforward. An electric discharge occurs between the two separate surface boundaries of a tool electrode and a work-piece. This is probabilistic but generally occurs at the closest point between the two facing surfaces. Figure 5.2 describes the material removal mechanism by single discharge. A tool electrode and a work-piece are electrically charged opposite: generally a tool electrode is positively charged and a work-piece is negatively charged in the figure. When a high voltage potential is built in the gap, the dielectric fluid is polarized due to the intense electromagnetic flux. If the dielectric resistance is overcome by this electric field, a plasma channel is formed and the electric current is allowed to flow. As a result, an electric discharge called a spark occurs. This single discharge has high thermal energy with temperature in the range of 8000 to 12000 degrees Celsius [77]. This thermal energy works as a heat source and material from the work-piece and the tool electrode is removed by melting or vaporization. Vaporized gas builds a bubble due to the pressure of the dielectric fluid. When the pulse is turned off, this gas bubble collapses and ejects debris into the dielectric fluid. This procedure is repeated in a high frequency ranging from 2000 to 500,000 a second [78]. Ideally, the tool wears at a much lower rate than material is removed.

Material removal by the single discharge makes a cavity and the workpiece cavity shape can be simplified as hemisphere. Because the discharge occurs in very short time, the removal volume is very small. However, a large number of electric discharges are involved at high frequency and the designed shape is machined into the workpiece. The radius of the hemisphere is proportional to the thermal energy. The various parameters like the peak current size, the voltage and the discharge duration time affect the size. The influence of each parameter will be discussed more in the next section.

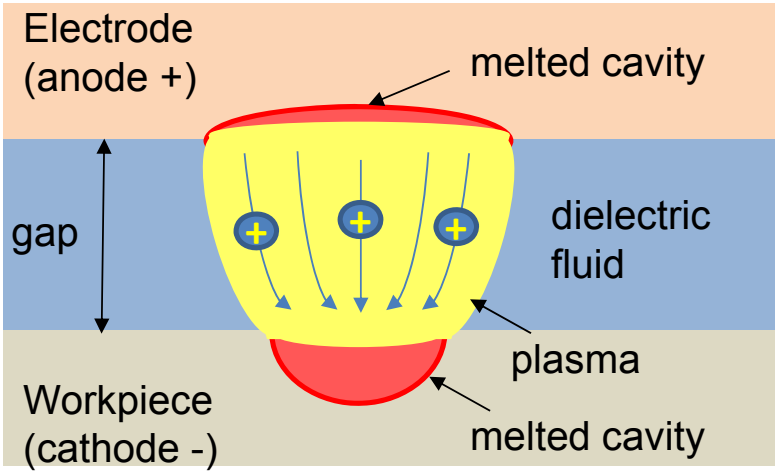


Figure 5.2. Material removal by electric discharge

5.2.1 Die sinking EDM and wire-EDM

According to the tool electrode shape and related components, most EDM machine tools can be classified as die sinking EDM or wire EDM.

Die sinking EDM is also called ram EDM or sinker EDM. In this type, the electrode serves as a male cutting tool and has the opposite shape of the target female shape design. Hence the tool electrode is a custom designed workpiece and machining processes are required to fabricate the electrode out of electrode material. During the operation, a work-piece and electrodes are immersed in dielectric fluid and controlled to be spaced with specific gap distance from each other. With an electric discharge occurring in the gap, the workpiece is machined and generally blind cavities are made. Because precise gap control is required for machining, a servo mechanism for tool head in feed motion is required for die-sinking EDM as shown in Figure 5.3 (a).

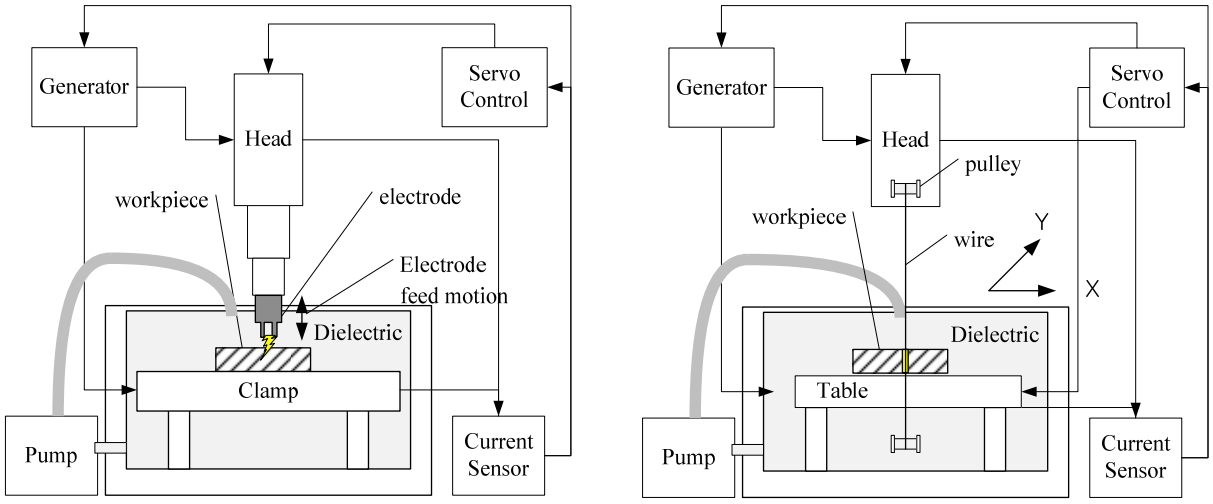
Wire EDM uses a spool of thin metal wire as the tool electrode. The machining shape is not defined by the electrode shape but by the NC controlled wire motion in two or more degrees of freedom. Hence, fabrication of the tool electrode is not required for this type of EDM. According to the required surface quality and machining performance, the thickness of wire can be varied. Instead of precise servo control of tool head in feed, a wire-EDM machine provides more accurate and complex multi-axis control and continuous wire feeding mechanisms. And instead of blind cavities, various profiles or through holes are generally machined with wire-EDM. More complicated shapes like tapered walls or ruled surfaces can be fabricated with more sophisticated motion control. Because clean wire tool is fed by a continuous wire drive, tool electrode wear is trivial compared to die-sinking EDM and once the wire has passed through the workpiece, it's discarded. The wire-EDM machine is described in Figure 5.3 (b).

Both die sinking EDM and wire EDM are important machining processes for molds and dies. However the energy consumption of these processes is not well known and only a few citations in the literature are available about this subject [79] [80] [81]. Die sinking EDM is more distinct

from conventional machining processes and is more influential in terms of the cycle time than wire EDM. By contrast, while wire EDM is also a thermal machining process, its machining mechanism is very similar to that of the milling operation in that the tool moves through the workpiece which is moved by table axes. Hence, knowledge of both processes is needed for understanding wire EDM operation and it can expected that the knowledge of the two processes can be expanded to wire-EDM operation. Considering this, this research considers only die-sinking EDM in this study and wire-EDM will be held for further research.

5.2.2 EDM components

Figure 5.3 (a) describes the basic components of an EDM machine tool. A pulse generator controls the electric discharge cycle in the machine. This component generates a specific size, shape and frequency of electric pulses at high frequency. The generator also precisely controls duration time of each pulse and the interval between adjacent pulses. A servo controller controls the physical motion of the electrode. According to gap sensor information, this component controls the electrode position and maintains the appropriate discharge gap size. Because the discharge condition is very sensitive to this gap size, very precise and high speed motion control is required. In some machines, a servo controller provides an orbiting motion for more flexible machining. Dielectric fluid is contaminated with tool and work material debris during the operation and this contamination makes the operating condition unstable, which may lead to uncontrolled sparking damage on the workpiece. Hence a pump circulates the dielectric fluid under high pressure. This also helps to flush debris from the gap.



(a) (b)

Figure 5.3. (a) Die sinking EDM and (b) 2 axis wire-EDM

The performance and the quality of the EDM operation are the integrated result of these components. Hence, understanding these components is important to analyze the EDM operation. However, the control mechanism of these components is the most important part of EDM

machine design and the information on the operation is not generally available for commercial machines. Hence, based on a theoretical model of EDM operations, machine tool characteristics need to be considered. Furthermore, because each machine tool developer uses different control strategy, experimental measurement and validation is required.

5.3 Process parameters in EDM

In Figure 5.4, a fishbone diagram of EDM operation parameters is depicted. Parameters related to the electrode are design input. Electric and mechanical constraints are operation parameters, by which the operation performance is controlled. This section will cover these parameters and their impacts on the EDM operation. Based on this, an analytical model will be presented which includes all the influence of these parameters.

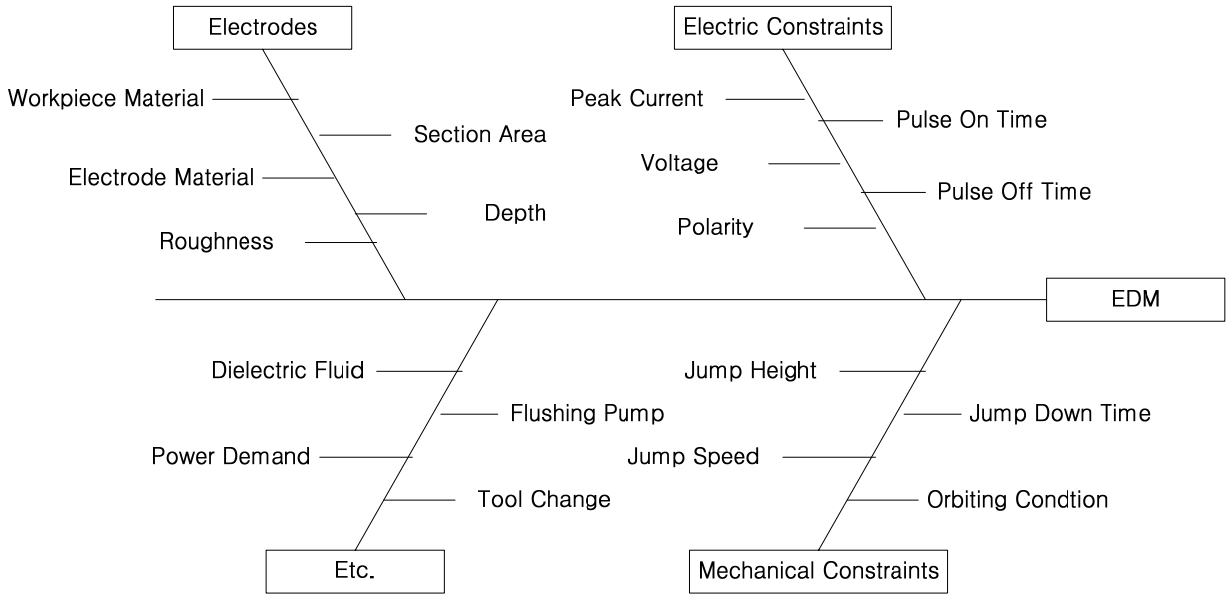


Figure 5.4. EDM operation parameters

5.3.1 Single discharge

Each pulse shape defines the single discharge in EDM. The thermal energy of the single discharge is proportional to the gap voltage, the peak discharge current, and the discharge duration time [82] [83]. Hence, the discharge energy of EDM can be expressed as below:

$$\text{Energy} = \begin{matrix}\text{discharge}\\ \text{current}\end{matrix} \times \begin{matrix}\text{discharge}\\ \text{voltage}\end{matrix} \times \begin{matrix}\text{duration}\\ \text{time}\end{matrix} \qquad (5.1)$$

The discharge current is known to be the most influential factor on MRR in EDM operations. Hence, the current size is generally used as a main control parameter. Figure 5.5 (a) shows that the peak current size is directly proportional to MRR across different duty cycles. Duty cycle is the percent of time spent on the electric discharge and will be explained in detail later. As the current size increases, MRR increases [84] [85]. This means that the current size affects the size of the crater described in Figure 5.2. Hence, some researchers compare the current size to the tool shape and size in milling operations. This explains why the lower peak value is used for a smoother surface in finishing and the higher value leads to more efficient removal rate in rough machining.

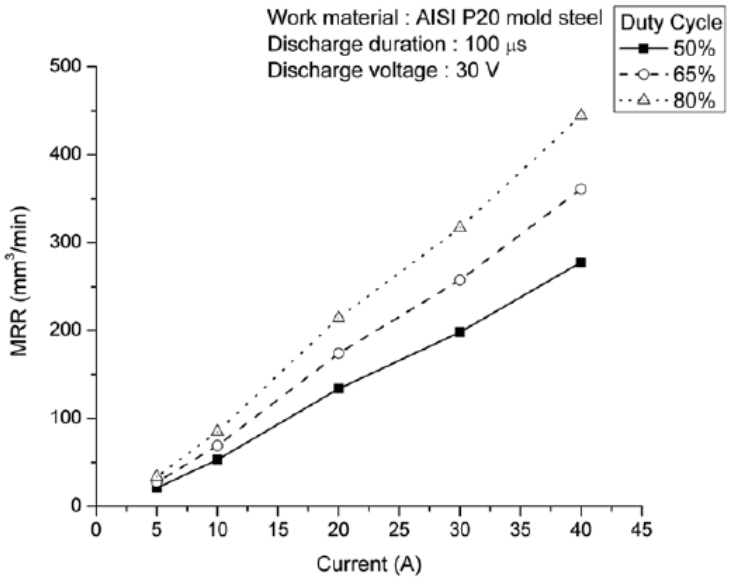


Figure 5.5. MRR versus current size for various duty cycles [86]

Discharge voltage also has similar influence on MRR. As higher voltage is applied, MRR increases. However, under a large electric resistance, even when the high voltage is applied, MRR doesn't change much as expressed in Figure 5.5 (b) [87]. Considering Ohm's law, the voltage can be assumed to be the dependent variable on the current.

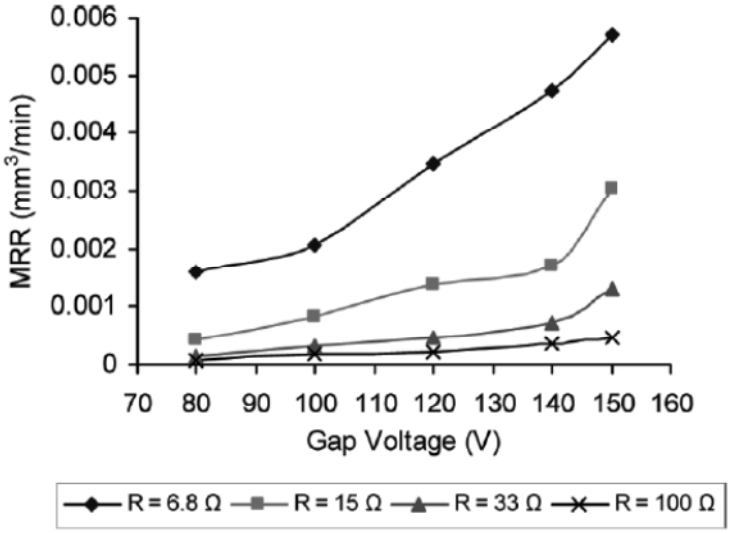


Figure 5.6. MRR versus discharge voltage for various electric resistances [87]

Because the applied thermal energy is proportional to the spark duration time, the discharge duration time also increases MRR [88] [89] [90] [91]. However, due to the increasing possibility of arcing with duration time, an optimal duration time exists to create the maximum MRR for every discharge current [92]. This is expressed in Figure 5.7 [93]. Considering this optimal value, the duration time is generally provided as a fixed value dependent on the current size in many EDM machines.

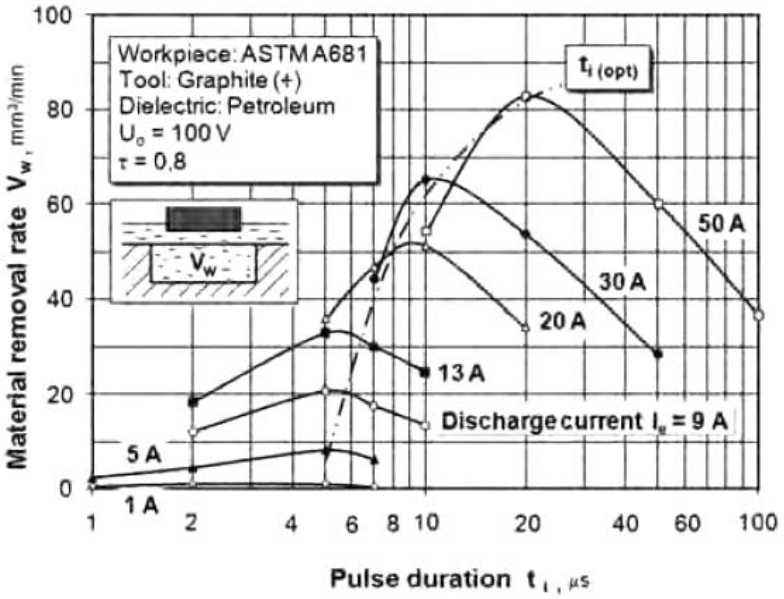


Figure 5.7. MRR and pulse duration time for different discharge currents [93]

The thermal erosion from the discharge energy is the main source of material removal in EDM. Hence, the thermal properties of the workpiece and the electrode material must be considered. The following empirical relationship for the metal removal rate in EDM is popular in many existing research studies [94] [95].

$$MRR_{wp} = I \times \left(6.64 \times 10^{-7} \times M_{wp}^{-1.23}\right) \ [m^3/s] \tag{5.2}$$

$$MRR_{tool} = I \times \left(1.78 \times 10^{-4} \times M_{tool}^{-2.28}\right) \ [m^3/s] \tag{5.3}$$

where, M_{wp} and M_{tool} are the melting point of the work-piece material and the tool electrode respectively, and I is the discharge current. Focusing on the melting point, MRR for the unit current can be expressed as the follows.

$$R_{wp} = 6.64 \times 10^{-7} \times M_{wp}^{-1.23} \ [m^3/As] \tag{5.4}$$

$$R_{tool} = 1.78 \times 10^{-4} \times M_{tool}^{-2.28} \ [m^3/As] \tag{5.5}$$

In these empirical equations, different material removal efficiencies for the workpiece and the electrode are expressed with different coefficients. These coefficients are for the positive polarity, in which a positive charge is on the tool electrode and the negative charge is on the workpiece. Negative polarity is generally used for wire EDM and will be not covered in this dissertation.

5.3.2 Discharge cycle

Electric discharge machining is controlled by the discharge cycle. As shown in Figure 5.8, this cycle defines the sizes, the on/off duration, and frequency of discharge pulses in terms of the voltage and the current. During the pulse-on time, the voltage potential builds a discharge condition and the resultant spark removes material from the workpiece and the tool electrode by melting or evaporation. As the duration of pulse-on status increases, more material can be removed. However, a long duration time causes a short circuit or arcing and damages the work-piece. To avoid this, the pulse-on time is limited and sufficient pulse-off time is required to stabilize the dielectric while the circuit control cuts off the voltage and current flow. These two pulse modes take turns for operations through the discharge cycle. When the voltage is on, discharge is delayed for a short time referred to as discharge waiting time. As a result, the discharge start time is not the same as the pulse on time as expressed in Figure 5.8. This waiting

time increases the actual non-machining time and as a result, the overall efficiency of the process is decreased.

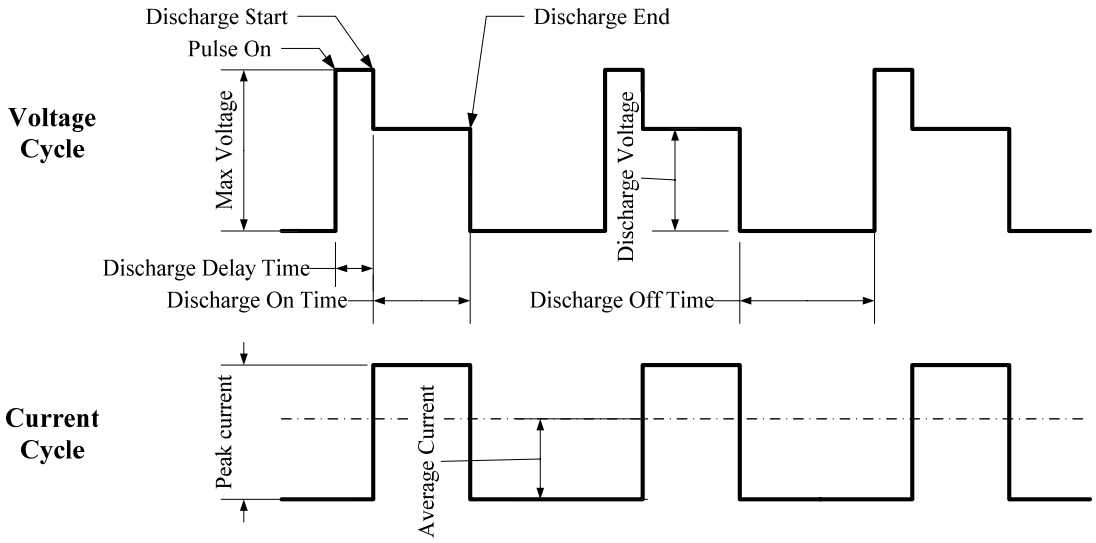


Figure 5.8. Discharge cycles of pulses in EDM

Single electric discharge duration time is very short and the material removal volume resulting from this is trivial. On the other hand, when the discharge condition is kept fixed, the single discharge can be assumed to remove the same volume of material. Considering this and the high frequency of the discharge cycle, one can reason that rather than using each discharge pulse as a unit of operation analysis, using the average values during a specific time interval is more effective. For this, average current size (I_{av}) can be defined as following:

$$I_{av} = I_{peak} \times \frac{T_{pulse_on}}{T_{pulse_on} + T_{pulse_off} + T_{discharge_delay}} \qquad (5.6)$$

Duty factor or duty cycle is the ratio of pulse on time to total time which is the sum of pulse-on time and pulse-off time. Because no machining occurs during the pulse-off time, this expresses how much time is actually spent in machining. Lower duty factor values mean longer time is wasted without productive activity. However, for flushing, the duty factor is always less than 1.

$$DF = \frac{T_{pulse_on}}{T_{pulse_on} + T_{pulse_off}} \tag{5.7}$$

If discharge delay time is trivial in equation 5.6, average current can be expressed with the peak current size and the duty factor.

$$I_{av} \approx I_{peak} \times \frac{T_{pulse_on}}{T_{pulse_on} + T_{pulse_off}} = I_{peak} \times DF \tag{5.8}$$

With the average current value and the actual operation time, equations 5.2 and 5.3 can be modified to:

$$\begin{aligned} MRR_{wp} &= I \times \left(6.64 \times 10^{-7} \times M_{wp}^{-1.23}\right) \times \frac{T_{pulse_on}}{T_{pulse_on} + T_{pulse_off}} \\ &= I_{av} \times \left(6.64 \times 10^{-7} \times M_{wp}^{-1.23}\right) [m^3/s] \end{aligned} \tag{5.9}$$

$$\begin{aligned} MRR_{tool} &= I \times \left(1.78 \times 10^{-4} \times M_{tool}^{-2.28}\right) \times \frac{T_{pulse_on}}{T_{pulse_on} + T_{pulse_off}} \\ &= I_{av} \times \left(1.78 \times 10^{-4} \times M_{tool}^{-2.28}\right) [m^3/s] \end{aligned} \tag{5.10}$$

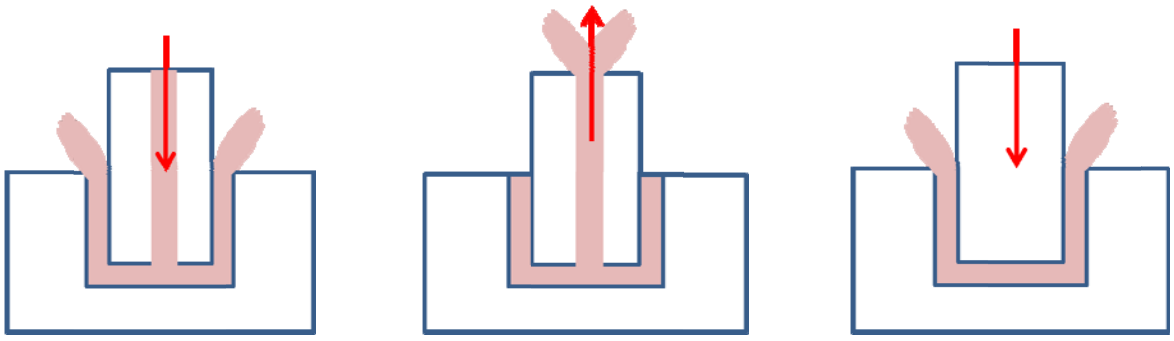
Based on this equation, the operation cycle time can be calculated as:

$$t_{cw} = \frac{Vol}{MRR_{wp}} = \frac{Vol}{I_{av} \times \left(6.64 \times 10^{-7} \times M_{wp}^{-1.23}\right)} \tag{5.11}$$

$$t_{ct} = \frac{Vol}{MRR_{tool}} = \frac{Vol}{I_{av} \times \left(1.78 \times 10^{-4} \times M_{tool}^{-2.28}\right)} \tag{5.12}$$

5.3.3 Gap control and flushing

Electric discharge is very sensitive to operating conditions and the gap distance is an important part of the electric discharge occurrence phenomenon. Based on the gap size and related dielectric conditions, an electric discharge can be categorized as four different types: long discharge, short discharge, spark, and arc. Except for the spark, other types cause inappropriate influence on the operation: longer cycle time or damage to the material. Hence, accurate control of the spark gap distance between tool electrode and work-piece is necessary. However, because the discharge condition varies during the operation, the gap size must be adapted to this variation. For this, high speed precise motion control is required for the servo controller.



(a) Pressure (Injection) flushing

(b) Suction flushing

(c) Jet or side flushing

Figure 5.9. Three types of flushing in EDM

Most research studies emphasize the importance of flushing in EDM operations [96] [77]. As material is removed during the operation, some of the removed material from the work-piece or electrodes accumulates as particles in the dielectric fluid. Because the material is conductive, this contamination increases the probability of unwanted arc discharge which damages the workpiece. To avoid this damage, more time is wasted for stabilizing the dielectric and the actual machining rate is decreased. Hence, it is important to flush the debris out of the discharge area and maintain the designed discharge condition.

Three flushing types are described in Figure 5.10: pressure or injection flushing, suction flushing, and jet or side flushing. Pressure and suction flushing use holes inside the electrode or the work-piece and pull or push the oil through the holes to flush. These methods provide high flushing efficiency, but the required hole structure demands sufficient electrode size. On the other hand, jet or side flushing method provides poor flushing efficiency. However, a supporting hole is not needed and small sized tool electrodes can be used with this method. Actually, for many electrode shapes, especially for small precise ones, jet or side flushing is the only available method. High demand for precision in molds and dies increase the importance of this method and as a result that of the EDM operation. Hence, this research focuses on the use of jet or side flushing.

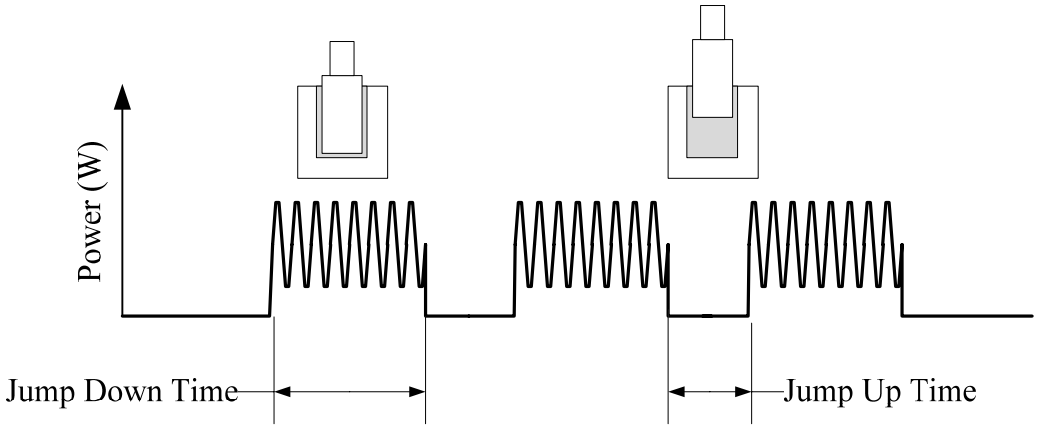


Figure 5.10. Electrode jump up/down time in jet flushing

In jet or side flushing, the tool electrode moves (or jumps) up and down periodically. When the electrode jumps to a specific height, clean dielectric fluid flows into the space the electrode previously occupied. When the electrode jumps down, the dielectric fluid in the space is flushed or pumped away with debris. As a result, debris density in the dielectric fluid is lowered. The section area of the electrode and the tool jump height define the flushing volume. Hence, the higher jump increases the flushing efficiency. On the contrary, if the electrode machines deeper, flushing efficiency gets worse because the debris is stuck around the active machining area. As expressed in Figure 5.10, electric discharges occur only during jump down time. Jump up time is non-productive and longer jump up time reduces the average current and MRR. However, short jump up time may lead to insufficient flushing efficiency and decrease the stability. Hence, some EDM manufacturers have adopted forced high jump for deep cavity machining. The average current and MRRs expressed before are modified as following to include the flushing action:

$$I_{av'} \approx I_{peak} \times \frac{T_{pulse_on}}{T_{pulse_on} + T_{pulse_off}} \times \frac{T_{jump_down}}{T_{jump_down} + T_{jump_up}} \tag{5.13}$$

$$\begin{aligned} MRR_{wp} &= I \times \left(6.64 \times 10^{-7} \times M_{wp}^{-1.23}\right) \times \frac{T_{pulse_on}}{T_{pulse_on} + T_{pulse_off}} \times \frac{T_{jump_down}}{T_{jump_down} + T_{jump_up}} \\ &= I_{av'} \times \left(6.64 \times 10^{-7} \times M_{wp}^{-1.23}\right) [m^3/s] \end{aligned} \tag{5.14}$$

$$\begin{aligned} MRR_{tool} &= I \times \left(1.78 \times 10^{-4} \times M_{tool}^{-2.28}\right) \times \frac{T_{pulse_on}}{T_{pulse_on} + T_{pulse_off}} \times \frac{T_{jump_down}}{T_{jump_down} + T_{jump_up}} \\ &= I_{av'} \times \left(1.78 \times 10^{-4} \times M_{tool}^{-2.28}\right) [m^3/s] \end{aligned} \tag{5.15}$$

5.3.4 Electrode material

Copper and graphite are the most popular materials for tool electrodes. As seen in the previous equations, the thermal property of the material is a decisive factor in the electrode wear or material removal. Because the tool electrode shape is copied into the workpiece, wear of the electrode is a critical issue for the process design. If the tool electrode is made of material which has a low melting point, the tool electrode is worn out faster and cannot perform the required operation. Hence, more electrodes are consumed to complete the process. Because graphite has high thermal resistance, a higher current can be applied with lower tool electrode wear and higher MRR of the workpiece. On the other hand, copper is much cheaper than graphite and cleaner to machine electrodes from.

Because of the thermal property, all the EDM process parameters are defined relative to the electrode material. After the selection of the material which satisfies the required wear ratio and fabrication methods, EDM engineers can design the other process parameters. During this process design, the material properties are assumed to be fixed constraints. There are additional factors for electrode characteristics in EDM operation: e.g., with respect to graphite electrodes, various specifications like the density and the grain size affect the machining performance and quality. However, such properties are beyond the scope of this dissertation and will not be covered here.

5.4 Cycle time variance consideration

As described in Chapter 4, the power demand of machine tools is not solely defined by the material removal process. Besides power demand for actual machining, constant power is used for peripheral devices and other functions. Most power demand of these peripheral devices is proportional to a corresponding operation time. Hence, reliable time estimation is indispensible to process analysis for estimating power demand. Actual cycle time is longer than that under ideal conditions. This holds true in EDM operations and the discrepancy between actual and ideal cycle time is larger than that in milling operation, generally the actual cycle time is two or three times longer in the EDM operation.

5.4.1 Time delay during pulse on time

Estimation of the material removal in EDM is straightforward in equation (5.2). However, as expressed in equation (5.9) and (5.14), actual MRR of the EDM operation should be considered including the discharge cycle and the electrode jump. In the actual process, this discharge cycle is not stable but dynamically varies. More time is wasted as the non-productive time from the discharge delay time, pulse off time, and jump up time. This waste of time is due to the discharge control and the servo control mechanism actions to avoid arcs or short circuit.

Figure 5.11 describes how the servo control manages the discharge delay time across different gap conditions [97]. As the discharge delay gets longer, non-machining time increases and actual MRR decreases. As a result, more power is wasted for the auxiliary devices during the

non-machining time. This implies that MRR estimated under ideal condition has limited effectiveness in practical operations.

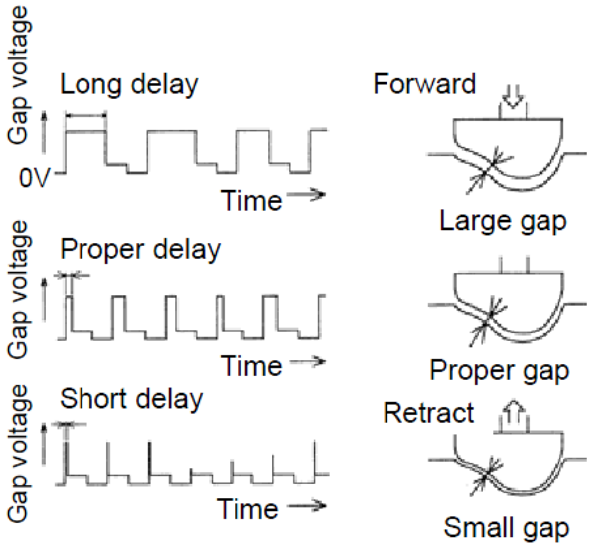


Figure 5.11. Servo feed control [97]

5.4.2 Inconsistent MRR

Actual MRR varies with the machining depth [98]. According to the example presented in Figure 5.12, the deeper the electrode moves, the more MRR decreases. One interesting way to improve cycle time estimation in EDM is to use different MRRs with incremental depth of machining [99]. However, this requires intensive experimental evaluation to address the variety of operating conditions.

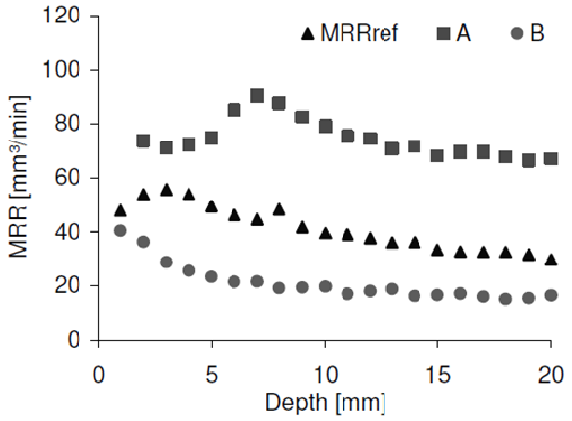
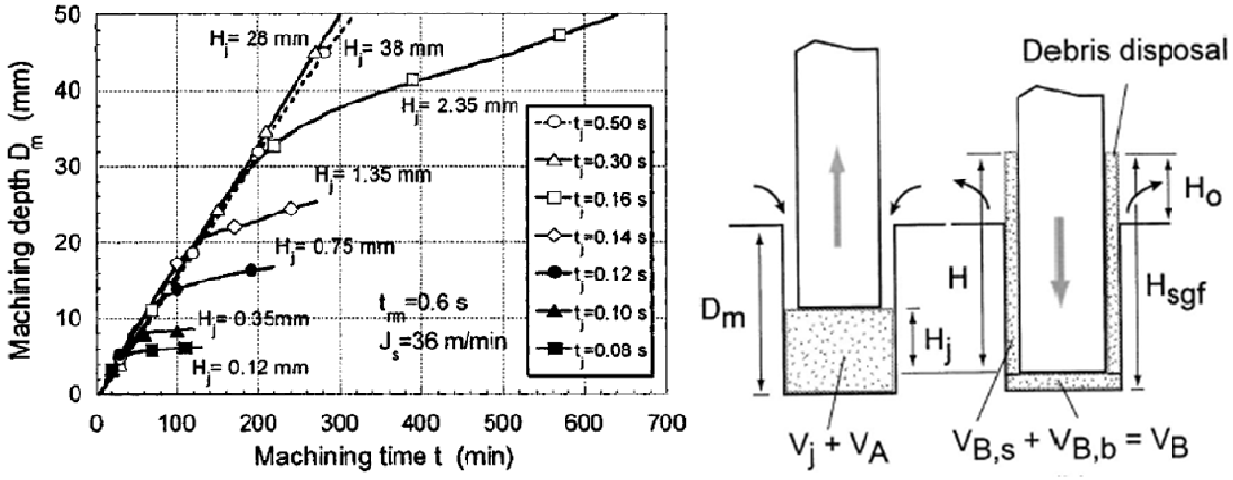


Figure 5.12. Machining depth and MRR change [99]

This is a costly and time consuming procedure and it is difficult to carry out without the EDM machine tool developer's support, which is hardly available in most cases. Hence, more practical methods are required that are easy to conduct in mold and die manufacturing.

Debris concentration in the dielectric is an important reason for the instability of EDM operation. Cetin et al. compared MRRs among different flushing conditions and claimed that a higher flushing rate results in higher MRR in EDM. As a result, they suggested the use of appropriate electrode jump conditions for effective EDM operation. In Figure 5.13, flushing conditions with different electrode jump height (Hj) were compared with regards to machining depth and corresponding time. It was found that removal performance is dramatically reduced with contamination density over a certain threshold [100]. Richardson et al. also added similar findings through their experiments [98]. According to these previous research works, two different MRRs must be considered in the EDM operation. Before the discharge breaking point, material can be removed with expected performance presented in the reference data of the machine. After the breaking point, the efficiency drops to less than 30% of expected. This explains why in some cases, the actual cycle time is almost three times longer than expected in EDM.



(a) (b)

Figure 5.13. (a) Jump height and machining depth relation in EDM and (b) schematics of flushing [100]

The discharge breaking point is defined as the point where the debris density does not decrease with a defined jump height. This point is important information for making an appropriate strategy for EDM operations. Assuming the breaking point is the saturated flushing condition as described in Figure 5.13 (b), this saturated condition and the breaking point are expressed as a function of tool electrode shapes, jump height and gap information as:

$$V_B = V_j + V_A = \frac{\pi}{4}\left(d_e + 2D_g\right)^2\left(H_j + D_g\right) \tag{5.16}$$

$$D_c = H_j \frac{\left(d_e + 2D_g\right)^2}{\left(d_e + 2D_g\right)^2 - d_e^{\,2}} + D_g \tag{5.17}$$

where, V_B, V_j, V_A, H_j, D_C, d_e, and D_g are fluid volume, the jump volume, the gap volume, jump height, discharge breaking depth, the diameter of electrode and the side gap size respectively. Only geometric parameters about the electrode shape, gap sizes, and the jump height are used in the equation. However, MRR is not considered in this model. Because the contamination speed is dependent on MRR, it seems reasonable to assume a higher MRR leads to faster contamination and shallower discharge breaking depth. Considering dielectric contamination and the steep decline of MRR, it is apparent that a fixed jump height is not appropriate for efficient EDM operations. Adaptive control of discharge pulse and jump height can be a way to address this inefficiency and to improve EDM performance [101] [102]. However, for the control logic, a relevant analytical or empirical model is required to allocate the appropriate parameters for specific operating conditions.

5.5 Environmental impact of EDM

While various research has addressed energy consumption and environmental impact of the conventional machining processes like milling and turning, EDM has not been studied in detail yet and available information is very limited. Input and output streams for the EDM operation, are expressed in Figure 5.14. Various materials are involved and wasted in the operation. The material stream is driven by the material removal process and electric energy consumption for this process. Hence, detailed process analysis for energy consumption is required for the analysis of environmental impact of EDM.

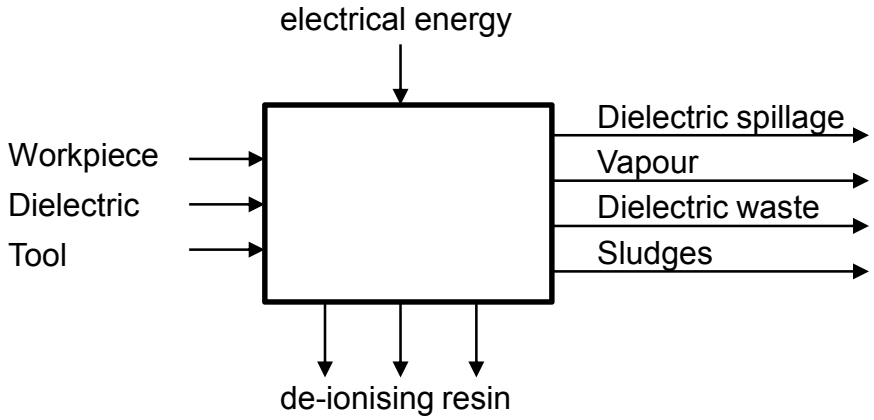


Figure 5.14. EDM ecological block scheme [82]

5.5.1 Energy consumption for material removal in EDM

As single discharge lasts only a short time period of tens to hundreds of milliseconds, tracking every single discharge to analyze the process operation energy consumption is infeasible. On the other hand, since discharge pulses turn on and off at high frequency according to the discharge cycle, we can assume a statistical average removal volume as the amount removed by a single discharge with the same discharge parameters. Based on this assumption, the MRR over a specific time interval can be used for the analysis. With the MRR, processing time and related power demand of components can be assessed and energy consumption can be calculated.

Considering two distinct MRRs proposed in the previous section and using MRR expressions in equation (5.14), the operation cycle time in each phase can be calculated as:

$$t_{cw_phase1} = \frac{AD}{MRR_{phase1}} = \frac{AD}{I \times \left(6.64 \times 10^{-7} \times M_{wp}^{-1.23}\right)} \times \frac{T_{pulse_on}}{T_{pulse_on} + T_{pulse_off}} \times \frac{T_{jump_down}}{T_{jump_down} + T_{jump_up}} \tag{5.18}$$

$$t_{cw_phase2} = \frac{A(D - D_c)}{MRR_{phase2}} = \frac{A(D - D_c)}{\mu \cdot MRR_{phase1}} \ (0 < \mu < 1) \tag{5.19}$$

$$MRR_{phase2} = \mu \cdot MRR_{phase1} \ (0 < \mu < 1) \tag{5.20}$$

$$t_{cw} = \begin{cases} \dfrac{AD}{MRR_{phase1}} & (D \le D_c) \\ \dfrac{AD_c}{MRR_{phase1}} + \dfrac{A(D - D_c)}{\mu \cdot MRR_{phase1}} = \dfrac{A(D + (\mu - 1)D_c)}{\mu \cdot MRR_{phase1}} & (D > D_c) \end{cases} \tag{5.21}$$

where t_{cw_phase1} is cycle time in phase 1, t_{cw_phase2} is in phase 2. MRR_{phase1} and MRR_{phase2} are MRRs in each phase, which can be estimated with the thermal property of the workpiece material or defined with measured values. On the other hand, actual machining time is needed to identify the energy consumed for actual removal. This can be expressed as:

$$t_{cw_mch} = t_{cw} \cdot \frac{T_{pulse_on}}{T_{pulse_on} + T_{pulse_off}} \times \frac{T_{jump_down}}{T_{jump_down} + T_{jump_up}} \tag{5.22}$$

5.5.2 Peripheral devices

While various machine tools have been analyzed and their components' power demand has been assessed in the case of milling operations, only a small amount of research is found for EDM [81] [79]. Kellens et al. investigated the power demands of EDM in different operation modes as shown in Figure 5.15. They measured different power demands for various machine statuses. They pointed out that the pump is the main power consumer ranging from 50 up to 72% of the total power consumption and that the current generation contributes only about 10%. They also compared time shares of three different modes and found that 66% of time is consumed for operation [80].

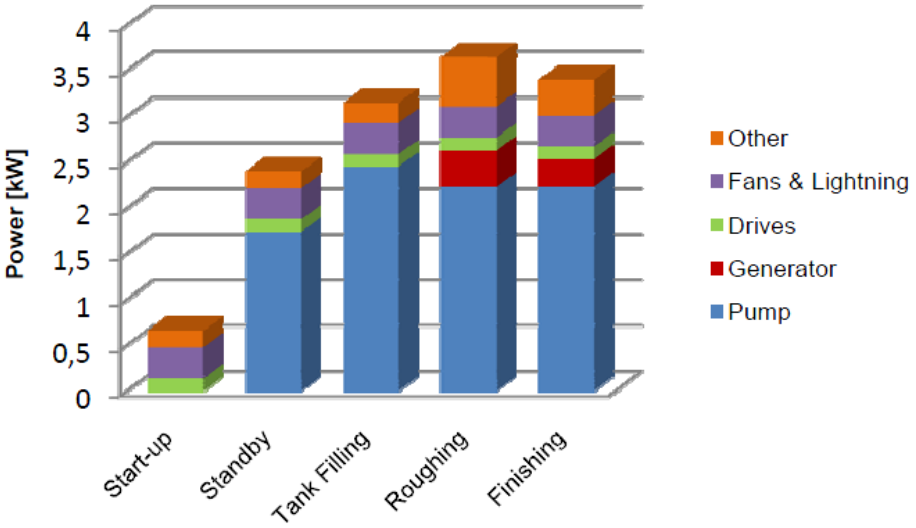


Figure 5.15. EDM power demands [80]

As depicted in Figure 5.15, the pump is the biggest power demanding component. The pump is circulating dielectric fluid under high pressure throughout the operation regardless of material removal status. Hence, if inappropriate process parameters were applied, a huge amount of energy can be wasted for running pumps during inefficient operation periods. On the other hand, power demand by peripheral devices during idling status is not ignorable. While this is just about 10% of total power demand, the amount of power is not insignificancy. Compared with power demand of the CNC milling machine in an idle status, this is almost same amount. Hence, some EDM developers provide monitoring systems for machine tool status to minimize the non-necessary power waste in the idle mode [103].

5.5.3 Waste of material

It is known that the tool electrode wear rate is much smaller than that of the workpiece wear rate for various reasons [104] [105]. When a metallic material is used for tool electrodes, the

remaining worn electrodes can be recycled or reused for smaller electrodes with additional fabrication. Hence, only worn out material contributes to the environmental impact. On the other hand, a graphite electrode in general cannot be reused or recycled. Furthermore, graphite electrodes may raise health issues due to dust generated during fabrication. During EDM operation, dielectric fluid is heated and vaporized between the gap and contaminated with debris of removed material. While contaminated dielectric is filtered to maintain clean operating conditions, vaporized dielectric may cause health problems.

The material stream is an important part of the environmental impact of EDM operations. Besides the embedded energy in each material, toxicity also needs to be considered because of vaporization of material during processing. However, this research focuses on energy consumption as the biggest contributor to environmental impact and the material stream will not be covered here. However, the operation model suggested here can be used as an important part to measure the environmental impact by the material stream by providing a more reliable process analysis.

5.5.4 Energy consumption of EDM

The energy consumption of machine tools defined in equation 4.1 can be adjusted to fit EDM operations. For this, the electric discharge cycle and the jump cycle must be considered. Because of these two cycles, an EDM operating status changes much faster than that in a milling operation. As described in the previous sections, statistical expressions are more effective. Hence, use of the transient state is not relevant to EDM operation analysis and equation 4.1 can be simplified for EDM as:

$$E_{EDM} = E_{const}+E_{run\text{-}time\text{-}steady}+E_{cut} \tag{5.23}$$

Energy consumption in different phases can be defined with power demand and corresponding time. The power demand of peripheral devices like fans and lighting is treated as constant regardless of operational status. Hence, E_{const} can be expressed with this power. Power demanded by various pumps is the biggest portion of total power demand. Because the pump operates through the process regardless of discharge pulse cycle and jump status, the run time steady energy ($E_{run\text{-}time\text{-}steady}$) is defined with this power demand for the various pumps. Because of the large power demand of pumps, an increase in non-machining time results in a large energy waste in EDM operations. Lastly, the cutting state energy (E_{cut}) is determined by the power demand of the pulse generator. Then energy consumption of EDM operation can be expressed as:

$$E_{EDM} = P_{const} \times t_{cw} + P_{run\text{-}time\text{-}steady} \times t_{cw} + P_{cut} \times t_{cw_mch} \tag{5.24}$$

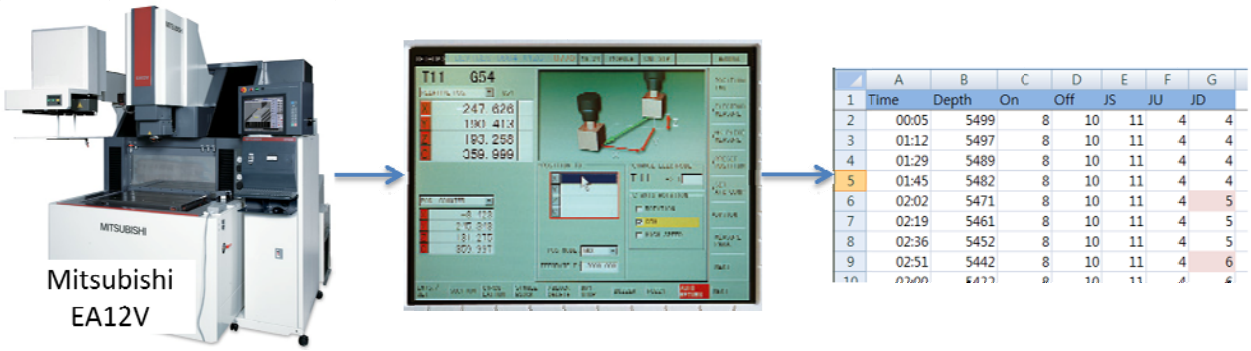
The following section describes experiments run to validate this relationship.

5.6 Machine data acquisition

Based on the literature reviewed, energy consumption models of EDM operations were proposed. To validate the models and the related assumptions, experiments were performed. Various operating conditions and electrode shapes were tested through these experiments. Due to the diversity in EDM machine tools and their operating characteristics, several different considerations were found.

5.6.1 Experiment setup and restrictions

A Mitsubish EA-12V EDM machine at the central fabrication complex of Laurence Berkeley National Laboratory (LBNL) was used in the experiment. Due to shop restriction of LBNL, a power meter was not used in this experiment. Instead, the monitoring screen was recorded and transferred to an Excel document and analyzed as shown in Figure 5.16.



	A	B	C	D	E	F	G
1	Time	Depth	On	Off	JS	JU	JD
2	00:05	5499	8	10	11	4	4
3	01:12	5497	8	10	11	4	4
4	01:29	5489	8	10	11	4	4
5	01:45	5482	8	10	11	4	4
6	02:02	5471	8	10	11	4	5
7	02:19	5461	8	10	11	4	5
8	02:36	5452	8	10	11	4	5
9	02:51	5442	8	10	11	4	6

Figure 5.16. EDM experimental setup and data acquisition

EA-12V supports a transistor controlled pulse with defined accuracy. Operations are automatically controlled by an embedded knowledge pack of electric discharge conditions (E-Pack) and mechanical conditions (M-Pack). E-Pack defines the peak current size, voltage, polarity, pulse on/off cycle, and jump up/down cycle in wide ranges. M-Pack manages effective side/bottom gap size according to the material properties and the electrode shape. Hence, parameter settings are restricted to E-Pack and M-Pack conditions.

In much research in the literature, electrode jump height was used as a control parameter over a narrow range of values. However, the EA-12V is designed to avoid a low flushing rate by low jump height for the small deep cavity. Instead, this machine provides an adaptive control for electrode jump. For the small section area of electrode, jump up height and jump down time are set to fixed values of 20mm and 45 seconds respectively. EA-12V also supports a fuzzy mode, in which the discharge cycle is automatically changed to adapt to discharge conditions. Fuzzy and normal modes were tested with three selected E-Pack conditions shown in Table 5.1.

Table 5.1. E-Pack conditions for experiments (Delta Z and Delta R from M-Pack)

E-Pack	ESEL	AUX	POL	IP (Amp)	ON (μsec)	OFF (μsec)	GAP	JUMP	JU (μm)	JD (μsec)	GAIN	OPAJ	DeltaZ (μm)	DeltaR (μm)
E114	SC	4	POS	35	1024	1536	0	11	600	250k	80	5	265	200
E115	SC	4	POS	25	512	1536	0	11	600	250k	80	5	163	116
E116	SC	4	POS	15	256	1024	0	11	800	250k	80	5	88	78

5.6.2 Experiment results and consideration

Figure 5.17 shows the measured machining depth and time relation and indicates MRR indirectly. A distinct decline of MRRs was found with discharge break points. For each side of the discharge breaking point, MRR shows consistent behavior and the corresponding regression line explains well each case with an R^2 of greater than 99%. This result is consistent with the assumptions expressed in equations 5.18~5.21.

According to Figure 5.17, for the same electrode, higher current does not always mean the shortest cycle time. In case of the 8mm diameter electrode, 25A current maintains normal speed longer than 35A condition. As a result, if the depth of machining is shallower than 13.7mm, the 25A current condition shows higher efficiency. In case of 10mm diameter electrode, the depth shallower than 14.5mm can be machined faster with 15A current than with 25A current. Furthermore, this result shows limitations of equation 5.17, which only considered geometric parameters. This implies the existence of an optimal discharge condition for EDM operations for two different MRRs.

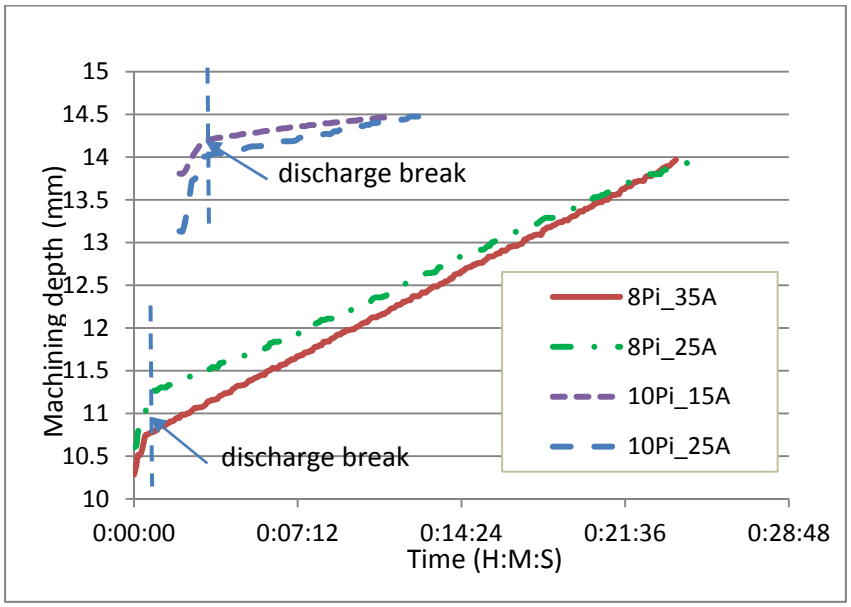


Figure 5.17. Material removal depth with the current sizes

Figure 5.18 compares the MRR in lower efficiency range. As described in the figure, MRR is proportional to the current size. This shows the possibility of estimating MRR with the current as in the ideal case.

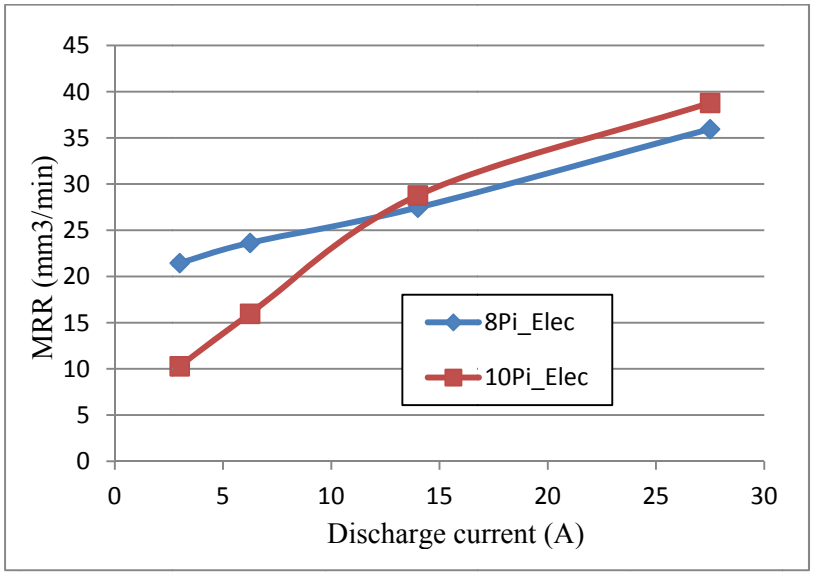


Figure 5.18. MRR across different current sizes

EA-12V provides a fuzzy mode for operation which supports higher machining efficiency with adaptive control. As seen in the example in Figure 5.19, MRR in fuzzy mode is kept to a fixed value, which is between the two MRRs introduced in Figure 5.17. While the current size and voltage do not change through the process, the duty factor keeps changing. In Figure 5.19 (b), duty factor increases from 0.4 to 0.7 while machining from 4mm to 7mm depth. After that, the duty factor decreases to 0.57 and holds constant.

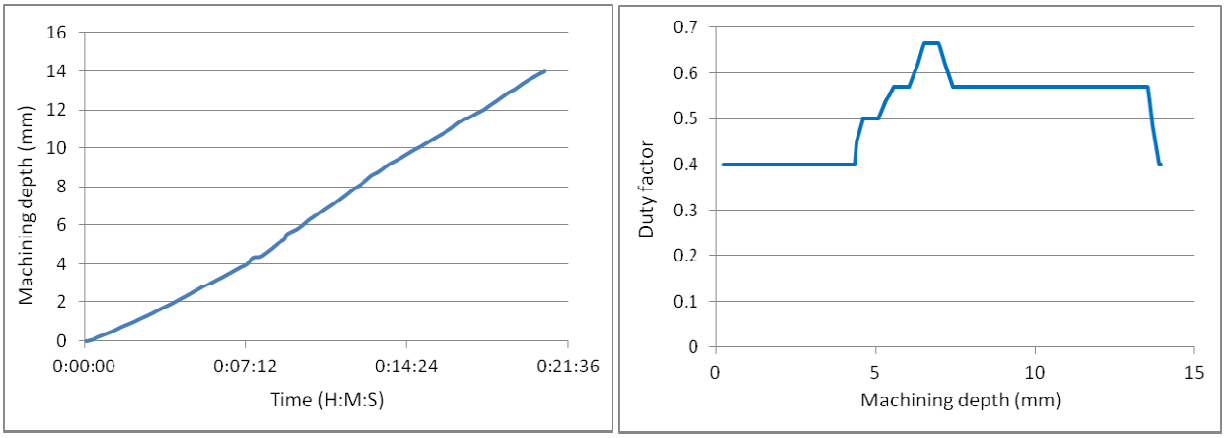


Figure 5.19. (a) Machining depth with time and (b) corresponding duty factor

It can be reasoned that the non-productive time is controlled by the duty factor to maintain the appropriate debris density in the dielectric fluid. However, with limited data, the fuzzy mode could not be analyzed sufficiently to be modeled here.

5.7 Modeling

Most CAM software tools support tool-path based operations for CNC milling, lathe, and W-EDM. Only few tools support die-sinking EDM for overcut or undercut verification. However, currently there is no CAD/CAM tool to support die-sinking EDM at the process design level, which requires handling both geometric and discharge conditions.

Figure 5.20 shows the information flow for the EDM process analysis which is proposed in this thesis. Geometric conditions include the electrode shape and gap definition for the side face and bottom. Discharge conditions are the pulse cycle information with the peak current and voltage. Besides these two categories of operation, the power demand structure of EDM machine components is used for the estimation. Energy mix and utility information is also included. Based on these input data, the material removal of the machine and power profile can be computed. As a result, the energy consumption and environmental impact of a specific EDM operation can be estimated. With this information, process engineers can avoid possible problems in operation and the associated environmental burden.

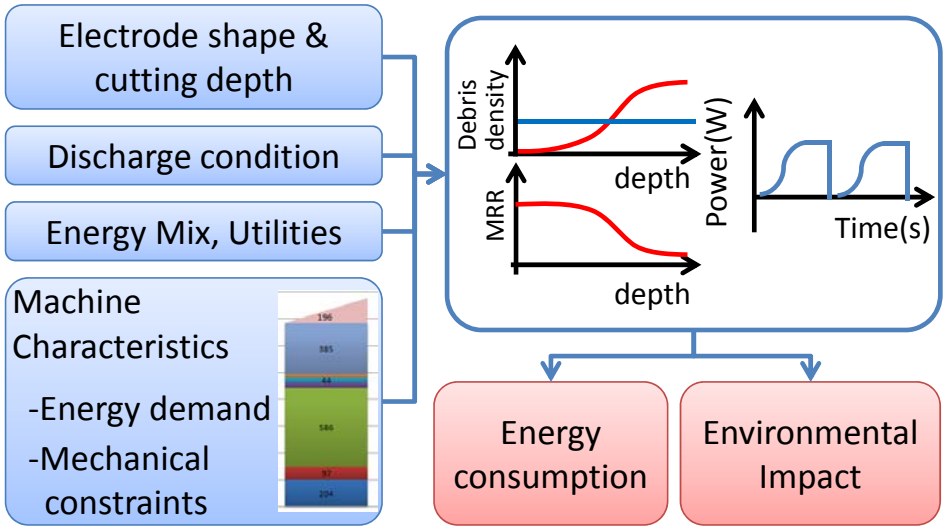


Figure 5.20. Information flow of EDM process simulation incorporating sustainability

5.8 Implementation

A software tool was implemented on the basis of Esprit CAM™ and its API. Table 5.2 lists the information available within Esprit CAM and that is provided as a database. Only the milling

operation and wire-EDM are managed as process objects in Esprit CAM. Hence, the die sinking EDM operation was implemented as a new process object. Because die sinking EDM is generally used for machining blind cavities, the pocket feature was selected as an interface to Esprit CAM for geometric information. Operation parameters regarding discharge condition and jump condition were designed to be input manually. For convenience, part of e-Pack and m-Pack knowledgebase was selected as a database for the EV-12V machine tool. This is shown in Figure 5.21.

Table 5.2. Process information supported by Esprit CAM.

Parameters	Process information
ESPRIT	section area, top/bottom depth, periphery length, volume, draft angle
EDM DB	Current size, voltage, pulse on/off time, jump up height, jump down time

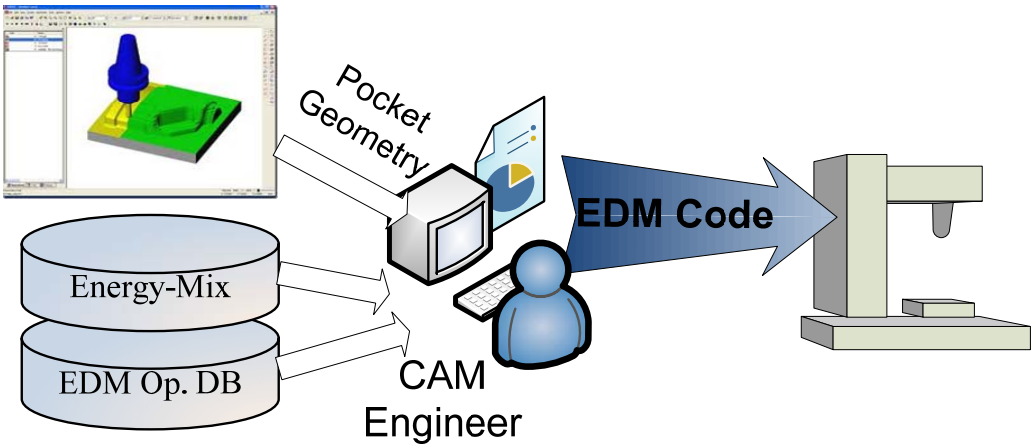


Figure 5.21. CAM-based EDM process simulation

5.9 Test case and analysis

Two different depths of cavities were compared across different flushing conditions. Table 5.3 shows the estimated cycle time and energy consumption for each case. While other conditions such as the peak current size, voltage, and pulse cycle were set to the same condition, different jump heights affect the flushing conditions and the resulting machining performance of EDM operations. The optimal conditions were found which minimize the energy consumption and are shown as shaded.

In the case of 30mm depth machining, higher jump was found to reduce both the cycle time and energy consumption. However, in the case of 20mm depth machining, the higher jump does not necessarily assure the better performance. When the jump is higher than 1.35mm, higher jump does not reduce the cycle time but increases the energy consumption. This is because the

higher jump is more than required for the operation and only increases the non-machining time and decreases MRR. This result shows why appropriate estimation is needed for EDM operations for cycle time and energy consumption determination.

Table 5.3. Cycle time and energy consumption across different jump height

Jump Height		0.35	0.75	1.35	2.35
Depth 30mm	Time (min)	-	830	410	180
	Ratio (%)	-	461%	228%	100%
	Energy (kWh)	-	21.1	10.7	4.8
Depth 20mm	Time (min)	1300	360	120	120
	Ratio (%)	1090%	300%	100%	100%
	Energy (kWh)	32.4	9.2	3.1	3.2

5.10 Conclusion

EDM is one of the most important processes in mold and die manufacturing. For more efficient and more environmentally benign mold making, EDM operations must be considered. In this chapter, an effective way of estimating the cycle time and the energy consumption during the EDM process was presented. An estimation tool for this was implemented on the basis of a commercial CAM software, Esprit CAM. With this simulation tool, various EDM operation conditions can be evaluated and compared.

Electrode shapes and jump conditions are influential factors on the EDM performance. The higher current leads to a higher MRR and reduces the cycle time in general. However, due to two different MRR ranges in the EDM operation, an optimal current size exists for the specific cavity shape which maximizes the performance. The estimation tool proposed in this thesis helps users to find this appropriate operating condition. As a result, more efficient and environmentally benign EDM operation can be achieved.

While this work suggests a way to support more environmentally benign EDM processes, there remains more to consider in the EDM operation analysis. The electrode shape may affect material removal rate in EDM in different way. The section area of electrodes was pointed out to affect MRRs in EDM operations [107]. According to the figure adapted from the work of Khan et al. in Figure 5.22, the longer periphery with the same section area causes lower MRRs regardless of the applied current. With more consideration of various process parameters, more effective support would be possible for EDM operations.

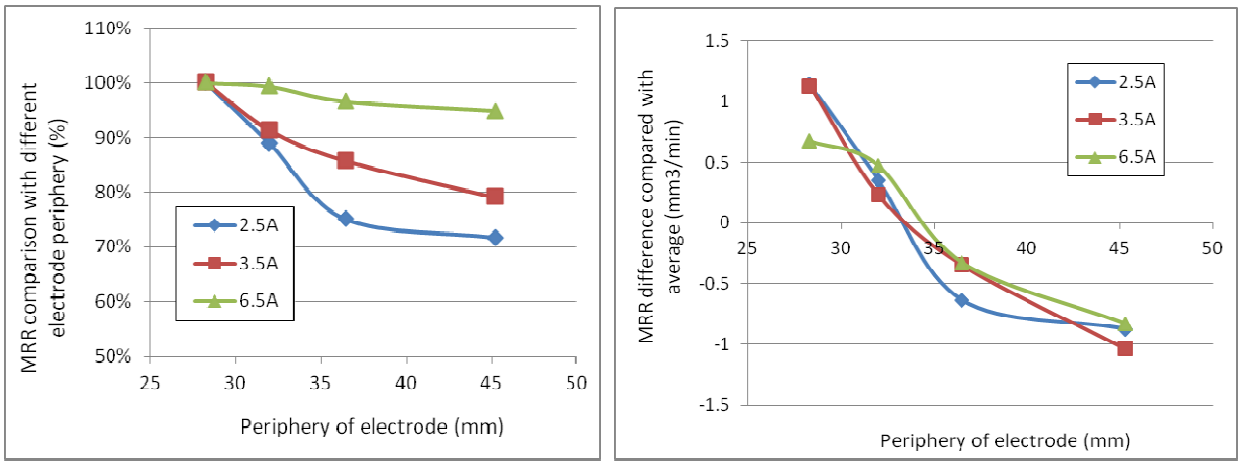


Figure 5.22. (a) MRR variation compared to circular area and (b) MRR variation across different peripherals with respect to average value [106]

Chapter 6

Environmental Impact of Mold Making

6.1 Introduction

The mold making process flow chart shown in Figure 6.1 is composed of several processes including milling and EDM. Milling processes are used to fabricate the workpiece and the EDM tool electrodes. In some cases, polishing processes are required after EDM operation. Because polishing and assembly are manually performed, most energy consumption is by milling and EDM processes. Hence, the energy consumed in this mold making process can be substantially determined as the sum of the energy consumed by milling and EDM processes and can be expressed as following:

$$E_{Mold} = \sum_{i=1}^{n} \left(P_{const,i} \times t_{cw,i} + P_{run\text{-}time,i} \times t_{cw,i} + P_{cut,i} \times t_{cw_mch,i} + P_{const,i} \times t_{idle,i} \right) \qquad (6.1)$$

where, $t_{cw,i}$, and $t_{idle,i}$ are operating time and waiting or set-up time respectively for the i-th machine tool used for mold and die manufacturing.

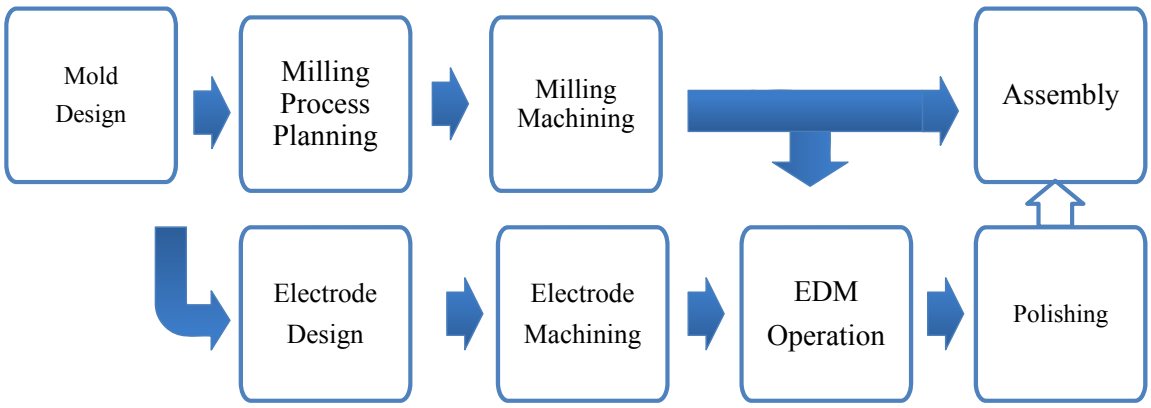


Figure 6.1. Mold making process flow with milling and EDM processes

On the other hand, molds and dies are very complex products so that generally a number of different components are fabricated. Hence, the environmental impact of mold making is the sum of all the impacts of the sub-components. For this, the environmental impact of each component

needs to be managed as a part of component information. Because of the many components needed in molds and dies, significant time is wasted for non-productive time like setup and waiting time. Considering the large fixed energy of machine tools, non-productive time also needs to be considered.

In this section, the evaluation tools explained in the previous chapters for milling and EDM processes will be summarized. An example will be presented for the energy consumption for a mold making processes. Considering the difference, the tradeoff between the two processes will be briefly explained for efficient process planning.

6.2 Software simulation in mold and die manufacturing

Mold making as studied here is a subtractive process. Various operations are sequentially executed and the workpiece is fabricated to a designed shape. This cannot be repaired without additional additive operations like welding. Furthermore, molds and dies are for such specifically designed products as to be produced only in small quantity for the same design. This means that it is not affordable to run test sample products as a way of finding optimal operation parameters, an approach frequently used in mass production like automobile manufacturing. Hence, process simulation is the most effective way to test possible operating conditions in a virtual environment and to design an optimal or improved process before execution.

Various software tools have been proposed for mold and die manufacturing. One important category of these software tools is the engineering expert system, which collects and distributes the knowledge of experts to improve the performance and quality of molds and dies [108]. Quotation of the cost of mold is another category which analyzes the complexity and difficulty of design and estimates the resources for mold making [109] [110] [111]. Energy consumption and environmental impact can be applied as new criteria to various engineering tools. Through this, more environmentally benign mold and die manufacturing could be achieved. Most of all, an appropriate estimation of the impact in the design phase would be the most effective.

6.3 CAM-based environmental impact estimation

Manufacturing impact evaluation tools were implemented for molds and dies on the basis of Esprit CAM software. The tools introduced in the previous chapters for CNC milling and EDM processes were integrated as a module in this tool. The analysis result is designed to be output to an Excel worksheet. Because this tool uses the milling process information in Esprit CAM, redundant user input can be avoided and environmental impact can be analyzed with ease. In case of the die sinking EDM process, users need to define corresponding pocket features and process parameters. However, this would allow the users to handle two important processes at the same time.

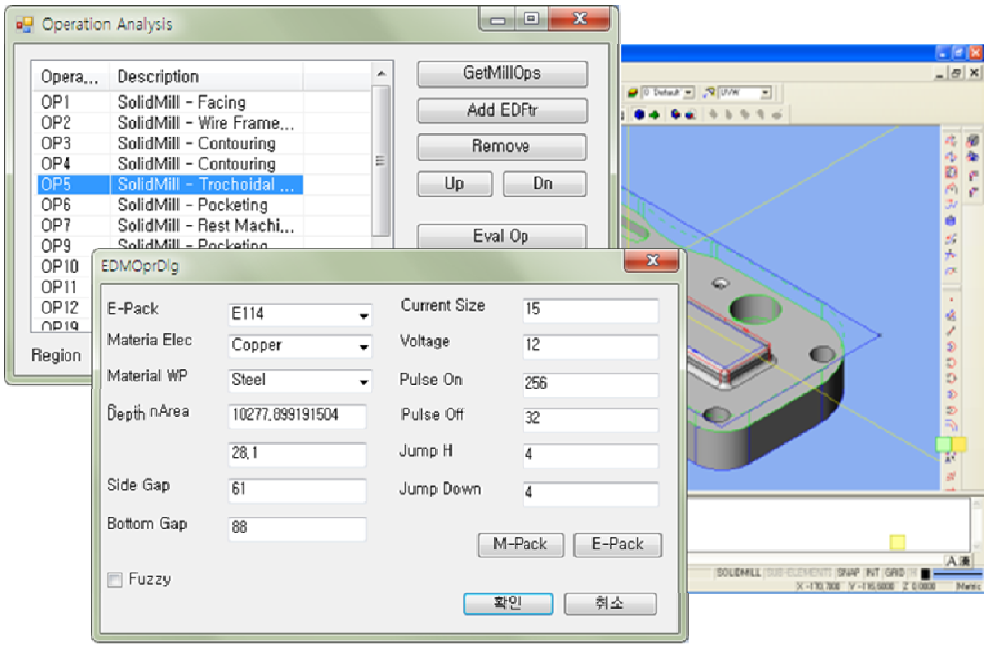


Figure 6.2. Process design dialogs with Esprit CAM

6.4 Test Case and analysis

The model used in chapter 4 was tested. To address the cycle time, five different tool paths were evaluated as seen in Table 6.1. Three 6mm diameter holes in the model were tested for the EDM operation. Three different current sizes and the two different MRRs were applied. The higher MRR was used before the discharge breaking point and the lower one was used after the breaking point. MRRs were acquired by regression analysis explained in chapter 5. The estimated cycle times were listed in Table 6.2. These tables show the lower MRR of the EDM operation and resultant long cycle time. Though the cylindrical cavity is small, the estimated cycle time is almost triple that used in a facing tool path listed in Table 6.1.

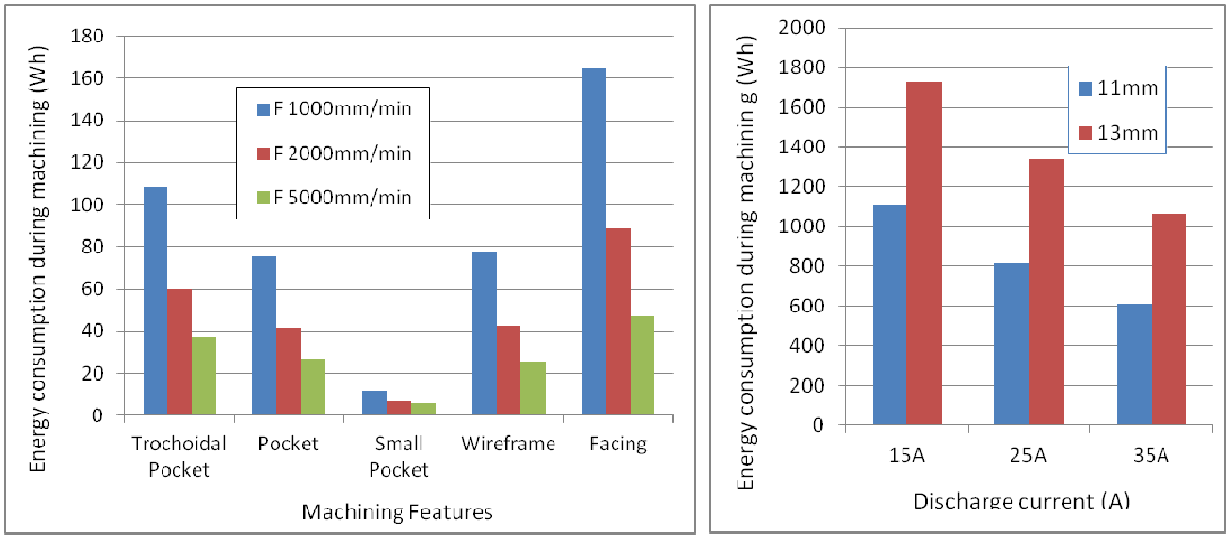
Table 6.1. Cycle time (sec) with different feed rates and tool path patterns in milling

	Trochoidal Pocket	Pocket	Small Pocket	Wireframe	Facing
F1000	454	316	49	324	690
F2000	235	163	27	167	348
F5000	115	83.2	18	80	147

Table 6.2. Energy consumption with different current size in EDM

Current (A)	MRR_Hi (mm^3/min)	MRR_Lo (mm^3/min)	Time (sec)
15	19.4	5.0	1813
25	28.4	5.9	1355
35	40.4	6.9	1040

Figure 6.3 shows the energy consumption for each condition. As seen in Figure 6.3 (a), for the same amount of removed volume, a high feed rate results in much less energy consumption. On the other hand, a much larger amount of energy is consumed in EDM operations was found in Figure 6.3 (b). As described in the figure, a 2mm depth difference was found to increase by almost 50% of the energy due to lower MRR in the deep cavity. Power break down data in Figure 5.15 was used for this estimation. According to this, the overall power demand of EDM is much larger than that of the CNC milling machine, which was about 1000W in the experimental result in Chapter 4.

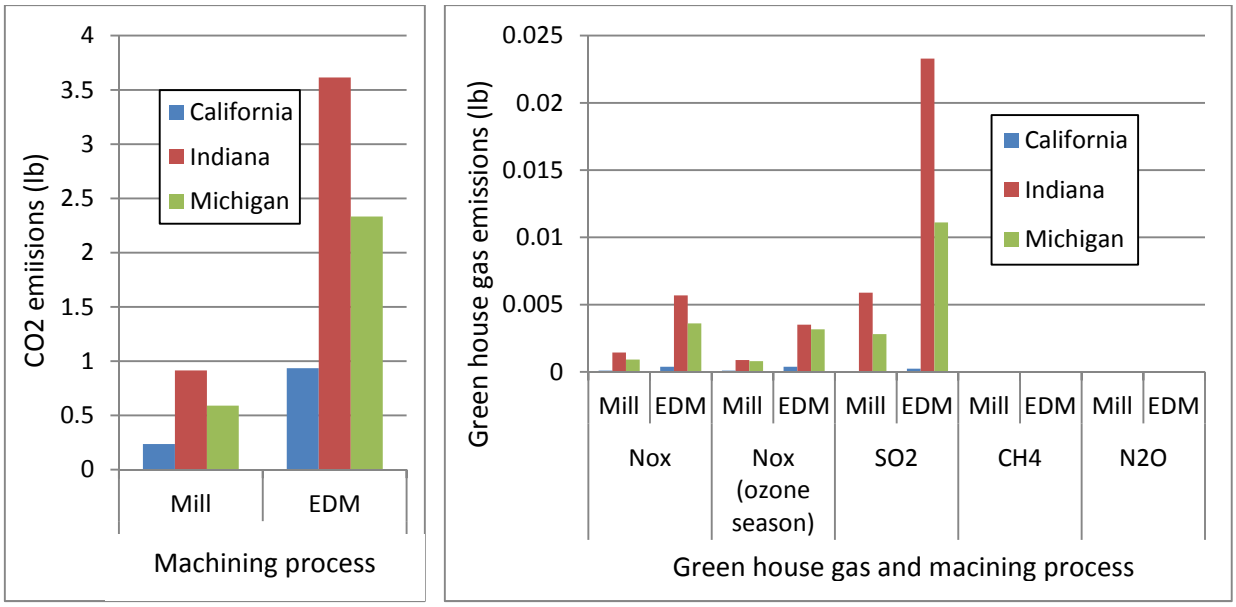


(a) Energy consumption of CNC milling machine

(b) Energy consumption of EDM machine

Figure 6.3. (a) Energy consumption in the CNC milling process with five different tool paths and (b) in the EDM process for two depths of cylindrical cavities with three current sizes

Figure 6.4 shows the GHG emissions by the two processes estimated over three different states of California, Indiana, and Michigan. Due to the dominant amount of CO2 in GHG emissions, CO2 emissions were distinguished in Figure 6.4 (a). GHG emissions from EDM operations are much larger values than from milling operations. Due to a more environmentally advantageous energy mix, the GHGs emissions in California were estimated to be much lower than those in the other states for the same mold making operations.



(a) CO2 emissions (b) Non CO2 GHGs emissions

Figure 6.4. (a) CO2 emissions and (b) other GHGs emissions by milling and EDM operations across three different energy mixes

6.5 Process planning

Due to the large power demand and low MRR of EDM, the shape to be fabricated with EDM must be carefully selected. Except for some specific cases like deep cavity machining in hardened steel or complex geometries, a milling process can replace EDM for machining. If part of a shape can be machined by milling, it is efficient and energy saving to use the milling operation with EDM as described in Table 6.3 [112].

Table 6.3. Process Comparative analysis adapted from [112]

Process	Processing time (min)				
	Setup	Machining	Program	Design	Total
HSM	27.0	83.1	70.0		180.1
EDM	85.0	519.8	125.0	30.0	759.8
HSM+EDM	39.5	354.4	105.0	30.0	528.9

A quotation for mold products is generally based on the estimated cycle time for each process. Hence, various methods are used for this ranging from a simple weight-based analysis to the feature-based complexity analysis [111]. Environmental impact or energy consumption can be treated in a similar way.

Poorly estimated process performance increases the risks regarding any generated environmental impact. Because of large tare energy in machine tools and different MRRs

between two processes, appropriate process arrangement and balancing is important to insure reduction of the environmental impact. With the tools suggested here, the possible environmental impact for each option can be estimated and possible environmental risks can be avoided in the process planning phase.

6.6 Conclusion

Environmental impact in the mold and die manufacturing was estimated for two important processes of CNC milling and EDM. Both processes are affected by many parameters in terms of performance and the likely environmental impact. CAM-based software tools were implemented as effective design tools to address complexity in the process analysis. Environmental analysis can be incorporated into the conventional mold and die manufacturing processes as additional evaluation criteria. Analysis and comparison of different process parameters within CAM software environment allows users to avoid possible risks and design more environmentally benign processes and molds.

Table 6.4. Comparison of milling and EDM processes

	Milling	EDM
MRR	High	Low
Power demand in machining	1.0~2.0kW	3.5kW
Power demand in standby	0.8kW	0.5~2.4kW

Table 6.4 compares two major mold and die manufacturing processes covered in this thesis. Power demand characteristics were compared with measured information from a Mori Seiki NVD1500 and the work shown in Figure 5.15. In both processes, high portion of tare energy was found. However, due to very low MRR nature of EDM, more consideration is required for EDM process.

Non-productive time such as setup and waiting time was not included in this tool. However, the information used in this thesis such as power demand break down data can be applied to a process monitoring system for the evaluation of non-productive time energy consumption. This can be enabled by the development of effective monitoring devices like RFID and MTConnect^{TM}. Through this, the environmental impact generated in mold and die manufacturing can be additionally reduced.

Chapter 7

Summary and Conclusions

7.1 CAM-based process analysis of molds and dies making

In this thesis, energy consumption during mold and die manufacturing was modeled with the two dominant processes of milling and EDM. This model was implemented in a software tool with CAM-based process simulation. CAM software tool is an indispensible part in modern mold and die manufacturing and CAM-based simulation is widely used to verify the process plan. The approach suggested here can be effectively incorporated into existing practice in mold and die production. On the other hand, milling and EDM processes also play important roles in other metal fabrication. Hence, the approach can also be applicable to any metal fabrication factory where milling and EDM processes are used.

An important issue of LCA in mold and die manufacturing is the absence of effective analysis tools. While more process specific analysis is required in mold and die manufacturing, currently available LCA tools provide rather high level comprehensive information generated with many deterministic models which are only useful in specific conditions. The information such LCA tools provide cannot be effectively applied to manufacturing practice. Furthermore, a large amount of the data requirement of LCA tools cannot be satisfied with limited resources at the mold and die factory level. The CAM-based tools suggested here can be a good alternative to this. This tool influences the existing CAM-based processes by adding new evaluation criteria: energy consumption and environmental sustainability.

One of the biggest challenges in the machining process analysis is the variability in the performance. Based on the operation parameters, the operation performance varies with respect to the cycle time and surface quality. Especially, the cycle time variability is critical due to large fixed (tare) power demand of general machine tools. This thesis considered various factors affecting this variability: acceleration and deceleration in CNC milling processes and dielectric fluid contamination in EDM processes. With these factors, the variability was included in the process analysis to provide more reliable process specific analysis results.

7.2 Future works

While the work in this thesis is generally available and useful to many mold and die manufacturers, there is a limit to cover the diversity in molds and dies. Furthermore, due to the position in the product development process, mold and die manufacturers have to address various customer requests. In this point, the work in this thesis would be just an early step in the road to environmentally benign mold and die manufacturing. In this section, promising future work for mold and die manufacturing will be presented.

7.2.1 Collaborative mold and die manufacturing

This thesis focused on the cutting process of milling and EDM operations. Other factors like coolant, cutting tools, and utilities were not covered in detail. These factors need to be included in further research. In case of utilities, overall input and output flow is measured but the influence on a specific process is not yet well-defined. However, its share of total energy consumption is huge and appropriate consideration is required.

Besides the two processes covered here, there are many other important processes in mold and die manufacturing. Mostly CNC milling is the dominant process but other processes replace CNC milling in some cases: e.g., grinding and diamond turning in optical precision molds and wire-EDM in precision thin plate dies. Especially, grinding is important in many manufacturing applications. Compared with the milling process, there is not much research on these processes. However, to support mold and die manufacturing, these processes cannot be ignored.

For more reliable environmental impact analysis, continuous update of information is required for the software tools. Tools like RFID and MTConnect™ are promising with respect to the life cycle data assessment of mols and dies. RFID can be used as an effective way of tracking molds and dies from manufacturing phase to their end of life. MTConnect™ can be incorporated into process management tools in mold and die manufacturing.

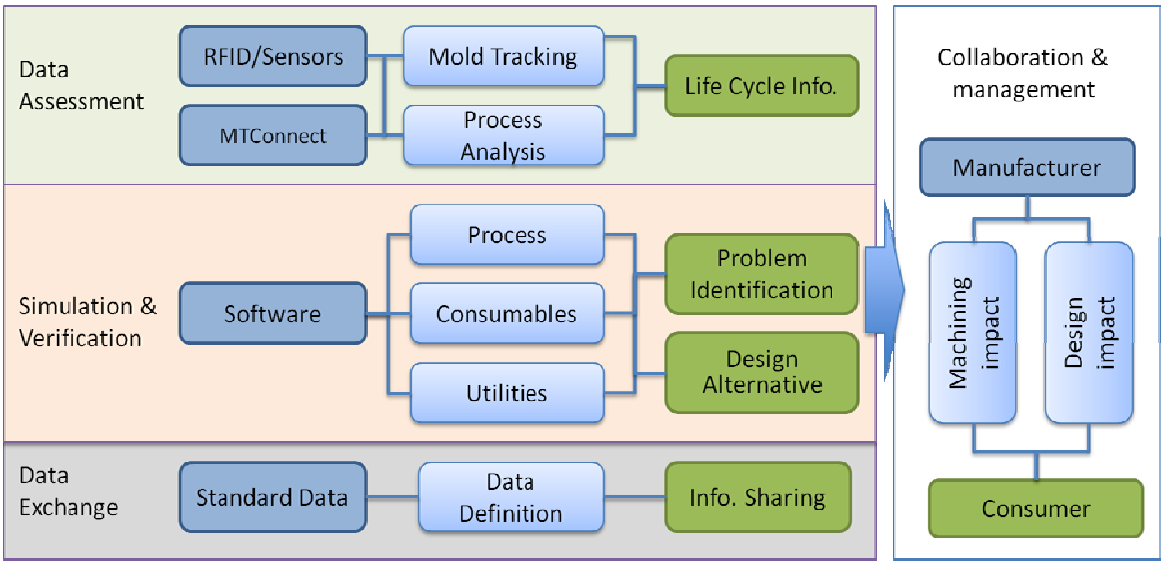


Figure 7.1. Future work to support collaboration and management in mold and die manufacturing

Mold and die manufacturers are the suppliers to various product developers. On the other hand, the manufacturers are also customers to the suppliers of various resources used in mold and die manufacturing. Hence, effective information sharing is necessary in this supply chain. However, there is no standard data which is accepted across different stakeholders with respect to energy consumption and environmental impact. Even the basic question of which information

is important and needed is not clear in many cases. This is a great barrier to environmental impact assessment through mold and die manufacturing. Hence, more standardized descriptions of manufacturing impact need to be developed for information sharing.

Figure 7.1 described three different categories of future work to support collaborative mold and die manufacturing with respect to energy consumption and environmental impact. Based on this, mold and die's environmental impact can be managed and manufacturers and consumers can collaborate more effectively in concern of more environmentally benign molds and dies. Furthermore, these software tools can be incorporated into the green building information system for more energy efficient factory management.

7.2.2 The leveraging impact of molds and dies

Molds and dies are consumed as production tools. Hence, the quality of the molds and dies is transferred to the products manufactured with these molds and dies. Precisely manufactured molds and dies generally produce more products and have longer lives without need of much maintenance. As described in Figure 7.2, various manufacturing phase information such as design, material, structure and precision influences use phase characteristics of quality, productivity, life span and cost. While the environmental impact in manufacturing phase may be increased for better quality of molds and dies, that in use phase and the total impact can be decreased more due to the improved quality in manufacturing phase. The leveraging impact of manufacturing on product performance was suggested [113]. In this perspective, the leveraging impact of molds and dies is worthy of consideration.

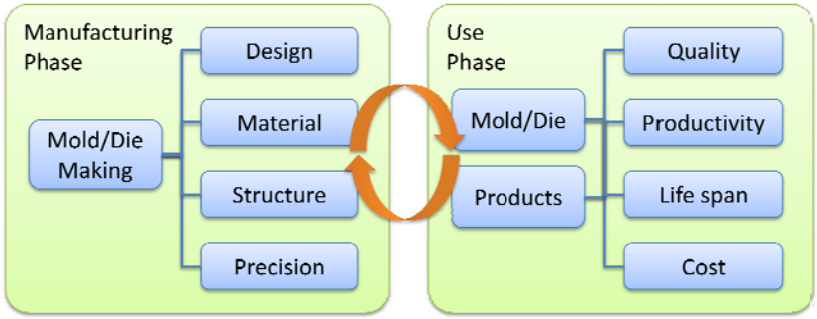


Figure 7.2. Integration of manufacturing phase and use phase information of molds and dies

The total impact can be expressed as following:

$$\text{Impact}_{\text{total}} = \sum \text{Impact}_{\text{manufacturing}} + \sum \text{Impact}_{\text{mold_use}} + \sum \text{Impact}_{\text{product_use}} \quad (7.1)$$

By combining manufacturing phase and use phase environmental impact, a complete life cycle analysis of molds and dies from production to the end of life and the history of the mold and die usage would be achieved.

Bibliography

1. British Petroleum (BP), "BP Statistical Review of World Energy June 2012", (2012)

2. Nuclear Energy Institute (NEI), "U.S. Electricity Production Costs and Components", (2012)

3. International energy agency (IEA), "Redrawing the energy-climate map", (2013)

4. S. Chu, and A. Majumdar, "Opportunities and challenges for a sustainable energy future", *Nature* **488** (2012)

5. J. Allwood, and J. Cullen, "Sustainable Materials with both eyes open", (2012)

6. The manufacturing institute, "The facts about modern manufacturing 8th edition", (2009)

7. International energy agency (IEA), "Worldwide trends in energy use in efficiency", (2008)

8. S. Brueske, R. Sabouni, C. Zach, and H. Andres, "U.S. manufacturing energy use and greenhouse gas emissions analysis", *Report for U.S. department of energy* (2012)

9. R. Hillebrand, "Life cycle policy for the chemical, petrochemical and pharmaceutical industries", *Technical white paper (Pepperl+Fuchs)* (2007)

10. CECIMO "Concept Description for CECIMO's Self-Regulatory Initiative (SRI) for the Sector Specific Implementation of the Directive 2005/32/EC (EuP Directive)", (2009)

11. R. Enparantza, O. Revilla, A. Azkarate, and J. Zendoia, "A Life Cycle Cost Calculation and Management System for Machine Tools", *13th CIRP Int. Conference on Life Cycle Engineering* (2006)

12. N. Diaz, M. Helu, S. Jayanathan, Y. Chen, A. Horvath, and D. Dornfeld, "Environmental Analysis of Milling Machine Tool Use in Various Manufacturing Environments", *IEEE Int. Symposium on Sustainable Systems and Technology*. (2010)

13. A. Munoz, and P. Sheng, "An analytical approach for determining the environmental impact of machining processes", *J. Materials Processing Technology* **53**, 3-4 (1995)

14. J. Dahmus, "Applications of Industrial Ecology: Manufacturing, Recycling, and Efficiency", *PhD Thesis, Dept. Mech. Eng., Massachusetts Institute of Technology, Cambridge, MA.* (2007)

15. A. Thiriez, and T. Gotowski, "An Environmental Analysis of Injection Molding", *Proc. of the 2006 IEEE Int. Symposium on Electronics and the Environment* (2006)

16. B. Neto, C. Kroeze, L. Hordijk, and C. Costa, "Modelling the Environmental Impact of an Aluminium Pressure Die Casting Plant and Options for Control", *Environmental Modeling & Software* **23**, 2 (2008)

17. S. Dalquist, and T. Gutowski, "Life Cycle Analysis of Conventional Manufacturing Techniques: Sand Casting", *Proc. Of the ASME Int. Mechanical Engineering Congress and RD&D Exposition*. (2004)

18. R. Schlosser, F. Klocke, and D. Lung, "Sustainabilty in Manufacturing – Energy Consumption of Cutting Processes", *Proc. the 8th Global Conference 85 on Sustainable Manufacturing* (2011)

19. W. Li and S. Kara, "An empirical model for predicting energy consumption of manufacturing processes: a case of turning process", *J. Engineering Manufacture* (2012)

20. D. Kong, S. Choi, Y. Yasui, S. Pavanaskar, D. Dornfeld, and P. Wright, "Software-based tool path evaluation for environmental sustainability", *J. Manufacturing Systems* **30**, 4 (2011)

21. O. Avram, and P. Xirouchakis, "Evaluating the use phase energy requirements of a machine tool system", *J. Cleaner Production* **19** (2011)

22. A. Dietmair, and A. Verl, "Energy Consumption Modeling and Optimization for Production Machines", *IEEE Int. Conference on Sustainable Energy Technology* (2008)

23. P. Wright, and D. Dornfeld, "Cybercut; A Networked Machining Service", *Trans. North American Manufacturing Research Institute, SME* **26** (1998)

24. D. Dornfeld, P. Wright, F. Wang, P. Sheng, J. Stori, V. Sundarajaran, N. Krishnan, and C. Chu, "Multi-agent Process Planning for a Networked Machining Service", *Trans. North American Manufacturing Research Institute* (1999)

25. H. Narita, H. Kawamura, T. Norihisa, L. Chen, H. Fujimoto, and T. Hasebe, Development of Prediction System of Environmental Burden for Machine Tool Operation (1st Report)", *Trn. the Japan Society of Mechanical Engineers. C* **71**, 704 (2006)

26. J. Heilala, S. Vatanen, H. Tonteri, J. Montonen, S. Lind, B. Johansson, and J. Stahre, "Simulation-based sustainable manufacturing system design", *Proc. of the 2008 Winter Simulation Conference* (2008)

27. G. Shao, D. Kibira, and K. Lyons, "A Virtual Machining Model For Sustainability Analysis", *Proc. of the ASME 2010 Int. Design Engineering Technical Conferences & Computers and Information in Engineering Conference*. (2010)

28. J. Camacho, "Worldwide tooling trends and production", *13TH Int. Special Tooling & Machining Association World Conference* (2010)

29. KITECH (Korea Institute of Industrial Technology), “Molds and dies needs”, (2004)

30. BizHospital, “Korea mold industry roadmap”, *available online http://www.bizhospital.co.kr*, (2012)

31. J. Kopac, “Achievements of sustainable manufacturing by machining”, *J. Achievements in manufacturing engineering* **34**, 2 (2009)

32. F. Pušavec, J. Kopač, “Sustainability Assessment: Cryogenic Machining of Inconel 718”, *J. Mechanical Engineering* **57**, 9 (2011)

33. H. Tönshoff, H. Oelschlager, and J. Petzold, “Life cycle cost orientation in the die and mold making industry”, *Proc. of 2nd Int. conference and exhibition on design and production of dies and molds* (2001)

34. T. Altan, B. Lill, and Y. Yen, “Manufacturing of Dies and Molds”, *CIRP Annals - Manufacturing Technology* **50**, 2 (2002)

35. P. Fonda, Z. Wang, K. Yamazaki, and Y. Akutsu, “A fundamental study on Ti–6Al–4V’s thermal and electrical properties and their relation to EDM productivity”, *J. materials processing technology* **202,** (2008)

36. P. Peças, and E. Henriques, “Intrinsic innovations of die sinking electrical discharge machining technology: estimation of its impact”, *Int. J. of Advanced Manufacturing Technology* **44** (2009)

37. F. Krause, “Energy efficiency in manufacturing: The role of ICT”, (2008)

38. C. Siegenthaler, A. Braunschweig, G. Oetteril, and S. Furter, “LCA software guide 2005: Market overview – software portraits”, (ÖBU, 2005)

39. M. Curran, and A Ciroth, “Life Cycle Assessment Handbook: A Guide for Environmentally Sustainable Products”, (Wiley, 2012)

40. G. Bhander, M. Hauschild, and T. McAloone, “Implementing Life Cycle Assessment in Product Development”, *Environmental Process* **22**, 4 (2003)

41. H. de Medina, “Eco-design for Materials Selection in Automobile Industry”, *Proc. 13th CIRP Int. conference on life cycle engineering* (2006)

42. R. Nowosielski, M. Spilka, and A. Kania, " Methodology and tools of ecodesign”, *J. Achievements in Materials and Manufacturing Engineering*, **23,** 1 (2007)

43. W. Yung, H. Chan, J. So, D. Wong, A. Choi, and T. Yue, “A life-cycle assessment for eco-redesign of a consumer electronic product”, *J. Engineering Design*, **22**, 2 (2011)

44. A. Morbidoni, C. Favi, M. Germani, "CAD-Integrated LCA Tool: Comparison with dedicated LCA Software and Guidelines for the Improvement", *Proc. the 18th CIRP Int. Conference on Life Cycle Engineering*, (2011)

45. T. Devoidere, W. Dewulf, W. Deprez, B. Willems, and J. Duflou, "Improvement Potential for Energy Consumption in Discrete Part Production Machines", *Proc. of 14th CIRP Int. Conference on Life Cycle Engineering* (2007)

46. M. Mori, "Power consumption reduction of machine tools", *2010 CIRP General Assembly CWG-EREE* (2010)

47. W. Li, A. Zein, S. Kara, and C. Herrmann, "An Investigation into Fixed Energy Consumption of Machine Tools", *Proc. the 18th CIRP Int. Conference on Life Cycle Engineering* (2011)

48. A. Vijayaraghavan, and D. Dornfeld, "Automated energy monitoring of machine tools", *CIRP Annals - Manufacturing Technology* **59** (2010)

49. V. Balogun, and P. Mativenga, "Modelling of direct energy requirements in mechanical machining processes", *J. Cleaner Production* **41** (2013)

50. N. Diaz, K. Ninomiya, J. Noble, and David Dornfeld, "Environmental impact characterization of milling and implications for potential energy savings in industry", *5th CIRP Conference on High Performance Cutting* (2012)

51. T. Gutowski, J. Dahmus, A. Thiriez, M. Branham, and A. Jones, "A Thermodynamic Characterization of Manufacturing Processes", *Proc. the 2007 IEEE Int. Symposium on Electronics & the Environment* (2007)

52. F. Draganescu, M. Gheorghe, and C. Doicin, "Models of machine tool efficiency and specific consumed energy", *J. Materials Processing Technology* **141** (2003)

53. W. Li, and S. Kara, "Unit process energy consumption models for material removal processes", *CIRP Annals - Manufacturing Technology* **60** (2011)

54. W. Li, S. Kara, and B. Kornfeld, "Developing Unit Process Models for Predicting Energy Consumption in Industry: A Case of Extrusion Line", 20th CIRP International Conference on Life Cycle Engineering (2013)

55. R. Steinhilper, S. Freiberger, F. Kübler, and J. Böhne, "RFID Integrated Adaption of Manufacturing Execution Systems for Energy Efficient Production", *20th CIRP International Conference on Life Cycle Engineering* (2013)

56. J. Peng, R. Guo, J. Li, Z. Shao, and J. Li, "Research on Tool Swept Volume in NC Simulation", *2011 Int. Conference on Electronic & Mechanical Engineering and Information Technology* (2011)

57. Anonymous, "Aspects of Energy Efficiency in Machine Tools", *Technical report of Heidenhain* (2010)

58. G. Quintana, J. Ciurana, and J. Ribatallada, "Modelling Power Consumption in Ball-End Milling Operations", *Materials and Manufacturing Processes* **26** (2011)

59. S. Tönissen, "Power Consumption of precision machine tools under varied cutting conditions", *Master's thesis* (2009)

60. E. Abele, T. Sielaff, A. Schiffler, and S. Rothenbücher, "Analyzing Energy Consumption of Machine Tool Spindle Units and Identification of Potential for Improvements of Efficiency", *Proc. the 18th CIRP Int. 280 Conference on Life Cycle Engineering* (2011)

61. H. Siller, C. Rodriguez, and H. Ahuett, "Cycle time prediction in high-speed milling operations for sculptured surface finishing", *J. Materials Processing Technology* **174** (2006)

62. A. Rangarajan, and D. Dornfeld, "Efficient Tool Paths and Part Orientation for Face Milling", *CIRP Annals -Manufacturing Technology* **53**, 1 (2004)

63. R. Coelho, A. Souza, A., A. Roger, A. Rigatti, and A. Ribeiro, "Mechanistic approach to predict real machining time for milling free-form geometries applying high feed rate", *Int J. Advanced Manufacturing Technology* **46** (2010)

64. J. Koelsch, "Unleash your CNC's power", *Manufacturing Engineering* **137**, 3 (2006)

65. S. Suh, S. Kang, D. Chung, and I. Stroud, "Theory and design of CNC systems", (Springer-Verlag, London. 2008)

66. M. Taniguchi, Y. Kakinuma, T. Aoyama, and I. Inasaki, "Influences of Downsized Design for Machine Tools on the Environmental Impact", *Proc. MTTRF 2006 Annual Meeting* (2006)

67. G. Copani, M. Leonesio, L. Molinari-Tosatti, S. Pellegrinelli, M. Urgo, A. Valente, and J. Zulaika, "Holistic approach for jointly designing dematerialized machine tools and production systems enabling flexibility-oriented business models", *19th CIRP Int. Conference on Life Cycle Engineering* (2012)

68. F. Wauters, and J. Mathot, "OEE Overall equipment efficiency", *White paper from ABB Inc.* (2002)

69. R. Schmitt, J. Bittencourt, and C. Scharrenberg, "Modelling Machine Tools for Self-Optimisation of Energy Consumption", *Proc. the 18th CIRP Int. Conference on Life Cycle Engineering* (2011)

70. C. Reich-Weiser, and D. Dornfeld, "A discussion of greenhouse gas emission tradeoffs and water scarcity within the supply chain", *J. Manufacturing Systems* **28**, 1 (2009)

71. W. Moomaw, P. Burgherr, G. Heath, M. Lenzen, J. Nyboer, and A. Verbruggen, "2011: Annex II: Methodology. In *IPCC: Special Report on Renewable Energy Sources and Climate Change Mitigation*", (2011)

72. U.S. Environmental Protection Agency, "eGRID2007 Version 1.1 Year 2005 Summary Tables." *available online http://www.epa.gov/egrid*, (2008)

73. S. Davis, G. Peters, and K. Caldeir, "The supply chain of CO2 emissions", *Proc. The National academy of science of the United states of America* **108**, 45 (2011)

74. R. Frischknecht, and M. Tuchschmid, "Energy supply: electricity mix updates", *2nd int. ecoinvent meeting* (2008)

75. H. Narita, N. Desmira, and H. Fujimoto, "Environmental burden analysis for machining operation using LCA method", *Proc. 41st CIRP conf. on manufacturing system* (2008)

76. X. Li, J. Wang, and W. Li, "Current State and Prospect of Micro-Machining", *Proc. IEEE Int. Conf. Automation and Logistics* (2010)

77. E. Guitrau, "The EDM Handbook", (Hanser Publications, 2009)

78. E. Jameson, "Electrical Discharge Machining", (Society of Manufacturing Engineers, 2001)

79. F. Klocke, S. Kamenzky, C. Deiss, A. Klink, and R. Perez, "Ecological Machine-Increase of Resource Efficiency and Cost Saving by Optimal Use of a Wire-EDM Machine", *Proc. ICMC* (2010)

80. K. Kellens, R. Dewulf, and J. Duflou, "Preliminary Environmental Assessment of Electrical Discharge Machining", *Proc. the 18th CIRP Int. Conference on Life Cycle Engineering*, (2011)

81. S. Dhanik, P. Xirouchakis, R. Perez, "A System for Resource Efficient Process Planning for Wire EDM", *Proc. the 18th CIRP Int. Conference on Life Cycle Engineering*,

82. S. Yeo, H. Tan, and A. New, "Assessment of waste streams in electric-discharge machining for environmental impact analysis", *Proc. of the Institution of Mechanical Engineers, Part B: J. Engineering Manufacture* **212**, B5 (1998)

83. J. Valentinčič, L. Duhovnik, D. Kušer, and M. Junkar, "Comparison of material removal in micro and conventional EDM", *Proc. the 9th Int. Conf. on Management of Innovative Technologies* (2007)

84. S. Joshi, and S. Pande, "Intelligent process modeling and optimization of die-sinking electric discharge machining", *Applied Soft Computing* **11** (2011)

85. Y. Zhao, X. Zhang, X. Liu, and K. Yamazaki, "Geometric modeling of the linear motor driven electrical discharge machining (EDM) die-sinking process", *Int. J. Machine Tools & Manufacture* **44** (2004)

86. S. Joshi, and S. Pande, "Thermo-physical modeling of die-sinking EDM process", *J. Manufacturing Processes* **12** (2010)

87. M. Jahan, Y. Wong, and M. Rahman, "Experimental investigations into the influence of major operating parameters during micro-electro discharge drilling of cemented carbide", *Machining Science and Technology*, **16** (2012)

88. F. Amorim, and W. Weingaertner, "Die-Sinking Electrical Discharge Machining of a High-Strength Copper- Based Alloy for Injection Molds", *J. of the Braz. Soc. of Mech. Sci. & Eng.* **26** (2004)

89. H, Singh, and D. Shukla, "Optimizing electric discharge machining parameters for tungsten-carbide utilizing thermo-mathematical modelling", *Int. J. Thermal Sciences* **59** (2012)

90. M. Sohani, V. Gaitonde, B. Siddeswarappal, and A. Deshpande, "Investigations into the effect of tool shapes with size factor consideration in sink electrical discharge machining (EDM) process", *Int J Adv Manuf Technol* **45** (2009)

91. Y. Lin, Y. Chen, C. Lin, and H. Tzeng, "Electrical Discharge Machining (EDM) Characteristics Associated with Electrical Discharge Energy on Machining of Cemented Tungsten Carbide", *Materials and Manufacturing Processes* **23** (2008)

92. D. DiBitonto, P. Eubank, M. Patel, and M. Barrufet, "Theoretical models of the electrical discharge machining process. II. A simple cathode erosion model", *J. Appl. Phys*. **66** (9), 1 (1969)

93. M. Gostimirovic, P. Kovac, B. Skoric, and M. Sekulic, "Effect of electrical pulse parameters on the machining performance in EDM", *Indian J. Engineering & Materials Sciences* **18** (2012)

94. E. Weller, "Nontraditional machining processes, 2nd edition", (Society of Manufacturing, 1984)

95. S. Kalpakjian, S. Schmid, "Manufacturing Engineering & Technology", (Prentice Hall, 2013)

96. P. Lonardo, and A. Bruzzone, "Effect of Flushing and Electrode Material on Die Sinking EDM", *Annals of the CIRP*, **48**: (1999)

97. M. Kunieda, B. Lauwers, K. Rajurkar, B. Schumacher, "Advancing EDM through Fundamental Insight into the Process", *CIRP Annals - Manufacturing Technology* **54** (2005)

98. M. Richardson, and Y. Gianchandani, "Real-time wireless monitoring of workpiece material and debris characteristics in micro-electro-discharge machining", *IEEE 21st Int. Conference on Micro Electro Mechanical Systems* (2008)

99. W. Vanderauwera, and B. Lauwers, "Time Estimation for Sinking EDM Operations", *Proc. the 16th Int. symposium on electromachining* (2010)

100. S. Cetin, A. Okada, and Y. Uno, "Electrode jump motion in linear motor equipped die-sinking EDM", *J. Manufacturing Science and Engineering* **125**, 4 (2003)

101. G. Xuesong, W. Yukui1, W. Zhenlong, and S. Debin, "Design and Research on EDM Fuzzy Control System Based on Mixed Programming of VC++ and MATLAB", *2011 Third Int. Conference on Measuring Technology and Mechatronics Automation (ICMTMA)* 1 (2011)

102. A. Hsue, and C. Chung, "Control Strategy for High Speed Electrical Discharge Machining (Die-sinking EDM) Equipped with Linear Motors", *IEEE/ASME Int. Conference on Advanced Intelligent Mechatronics* (2009)

103. Agie-Charmilles, "EDM Applications. Corporate Publications", (2006)

104. H. Xia, M. Kunieda, and N.Nishiwaki, "Removal Amount Difference between Anode and Cathode in EDM Process", *IJEM* **1** (1996)

105. W. Natsu, M. Kunieda, and N. Nishiwaki, "Study on Influence of Inter-electrode Atmosphere on Carbon Adhesion and Removal Amount", *IJEM* **9** (2004)

106. A. Khan, M. Yeakub Ali, and M. Haque, "A study of electrode shape configuration on the performance of die sinking EDM", *Int. J. Mechanical and Materials Engineering (IJMME)* **4**, 1 (2009)

107. K. Morimoto, and M. Kunieda, "Sinking EDM simulation by determining discharge locations based on discharge delay time", *CIRP Annals - Manufacturing Technology* **58** (2009)

108. M. Cakir, O. Irfan, and K. Cavdar, "An expert system approach for die and mold making operations", *Robotics and Computer-Integrated Manufacturing* **21** (2005)

109. B. Mikó, and F. Boór, "Enhancing of injection mould quotation accuracy", *Proc. Estonian Acad. Sci. Eng.* **13**, 2 (2007)

110. Z. Bouaziz, J. Younes, and A. Zghal, "Cost estimation system of dies manufacturing based on the complex machining features", *Int. J. Advanced Manufacturing Technology* **28** (2006)

111. N. Ravi, and N. Mukherjee, “An integrated framework for die and mold cost estimation using design features and tooling parameters”, *Int. J. Advanced Manufacturing Technology* **26**, 9-10 (2005)

112. M. Alam, K. Lee, M. Rahman, and K. Sankaran, “Decision algorithm for selection of high-speed machining, EDM or a combination for the manufacture of injection moulds”, *Int. J. Production Research* **40**, 4 (2002)

113. M. Helu, A. Vijayaraghavan, and D. Dornfeld, "Evaluating the relationship between use phase environmental impacts and manufacturing process precision”, *CIRP Annals - Manufacturing Technology* **60** (2011)

Appendix A

Estimation Software Tool

A.1 Esprit API

Esprit application programming interface (API) is designed on the basis of general Windows application development environment. VBA, Visual Basic and Visual C++ are supported as a programming language for this. Based on the selected language, expression of functions, variables, and predefined constants varies. Because Esprit API follows the general environment, other applications available in Windows environment, can be incorporated into one application software. Figure A.1 expresses general Windows application development environment and Esprit APIs.

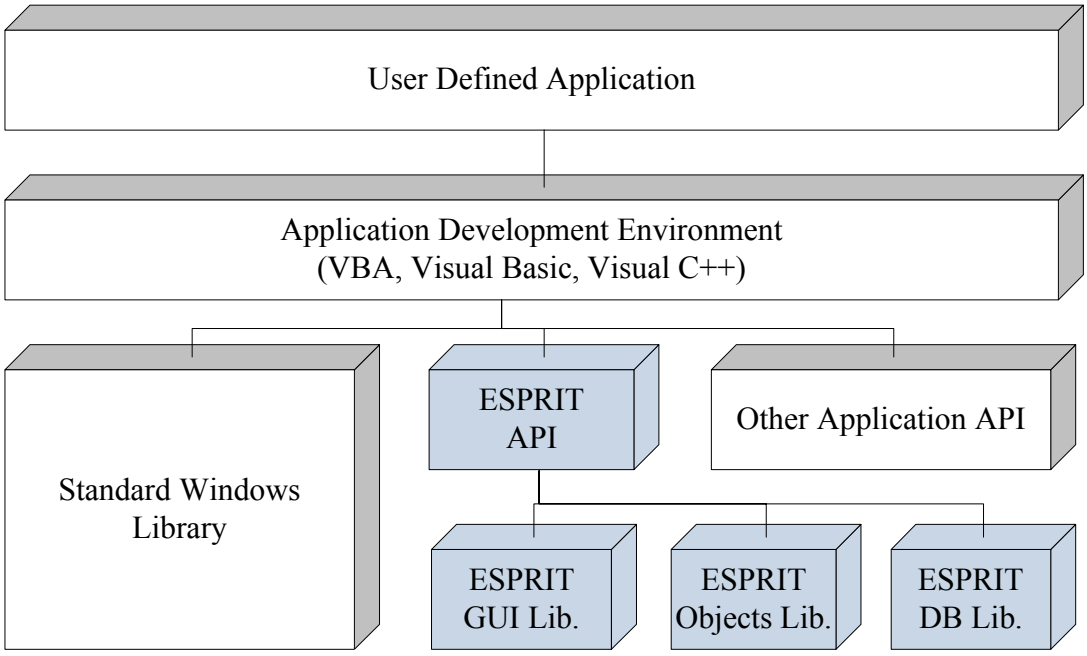


Figure A.1. Windows application development environment and Esprit API

API of Esprit CAM can be classified to three parts: graphic user interface (GUI), object, and database. API for GUI enables developers to customize existing interface and create additional interface specific to the application. API for object provides users with functions to handle various existing CAM objects such as operations and machines. Finally, API for database allows

developers to use existing knowledge and inventories about process technologies and cutting tools. As shown in Figure A.2, API of Esprit CAM supports milling, lathe, and wire-EDM processes. Hence, developing functions for these processes needs consideration of existing functions and objects. On the other hand, Esprit has no object or function for die sinking EDM and the object and functions for die sinking EDM need to be developed.

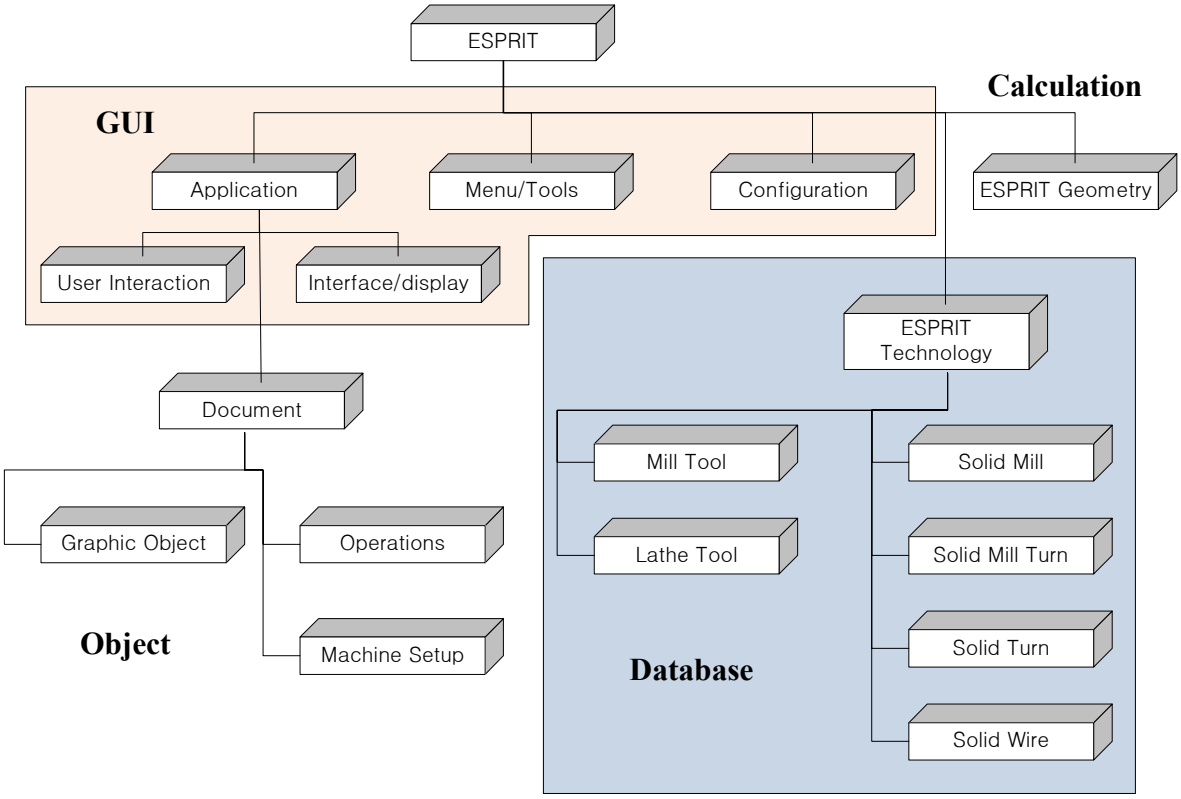


Figure A.2. Esprit API components

A.2 Graphic User Interface

Estimation software is designed to use the dialog box as the basic user interface. This tool can be executed regardless of the running status of Esprit CAM. When Esprit CAM is running, estimation tool is automatically linked to Esprit CAM. On the other hand, when Esprit CAM is not running, the estimation tool executes Esprit CAM when it is needed.

A.2.1 Operation Analysis Dialog

Operation analysis dialog is the top dialog of the estimation software tool. This dialog helps users collect all the active milling process objects and define EDM process objects. Based on the object list, the process sequence is reordered and unnecessary process objects are removed in this dialog. Figure A.3 shows operation analysis dialog and Table A.1 lists descriptions of the dialog components.

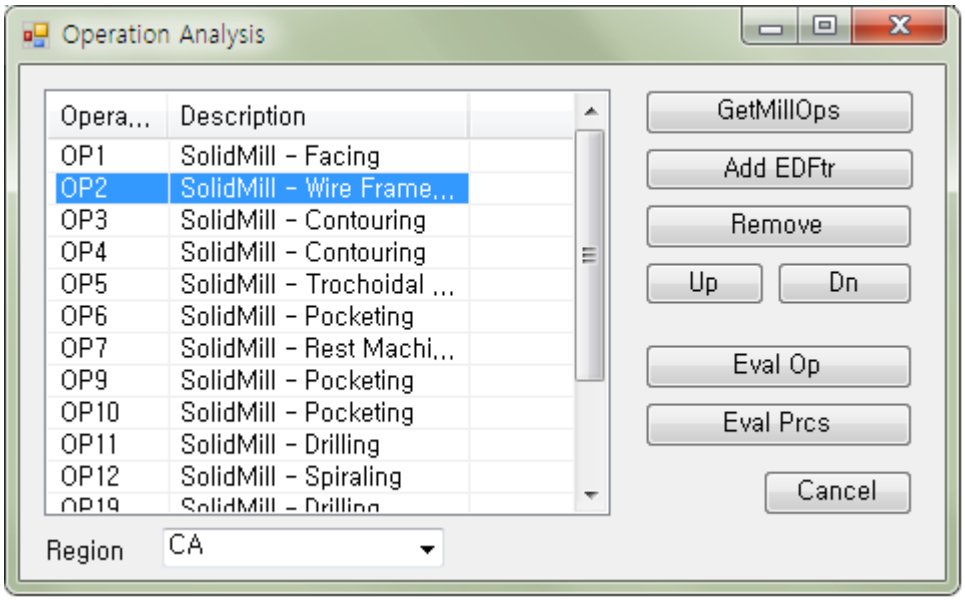


Figure A.3. Operation analysis dialog box

Table A.1. Operation analysis dialog UI components

GUI Component	Description
ListBox	List of active milling and EDM process objects is displayed with this component. Selected object in the list is displayed with blue color.
Region	This combo box shows current geographic location where the processes are carried out. This software assumes all the mold and die making processes are run at the same factory.
GetMillOps	This button allows users to search all the milling processes active in Esprit CAM workbench.
Add EdFtr	This button asks users to select pocket objects which will be machined with EDM.
Remove	This button executes removal of selected objects
Up/Dn	This button changes the position of selected object in the list box. Up button raises the order of selected objects and Dn button lowers the order.
Eval Op	This button opens an analysis dialog for selected process object.
Eval Prcs	This button creates summary worksheet with the energy consumption information of all the processes in the list.
Cancel	Close the dialog

A.2.2 Milling Operation Dialog

Milling operation dialog manages the analysis option of the selected milling operation. In this dialog, different operating conditions are defined and analysed. Analysis result is output to Excel worksheet.

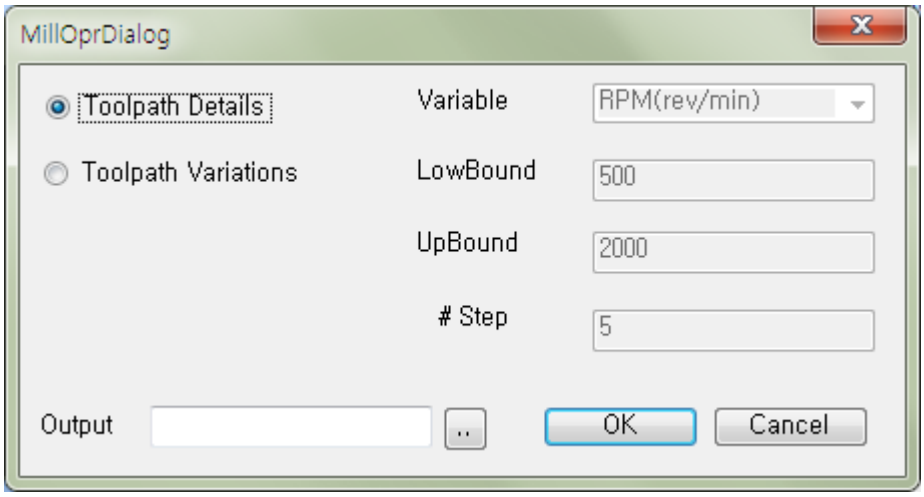


Figure A.4. Milling operation dialog box

Table A.2. Milling operation dialog UI components

GUI Component	Description
Toolpath details	This check box allows users to use existing operating conditions for analysis and output the result by each tool path block.
Toolpath variations	This check box allows users to apply different options to a specific operating parameter defined in the variable combo box.
Variable	This combo box allows users to select a operating parameter to test with different values. RPM, feed rate, and step size can be seleted.
LowBound	This textbox allows users to define lower boundary value for analysis.
UpBound	This textbox allows users to define upper boundary value for analysis.
#Step	This value defines the number of step in analysis. Based on this number, different values between lower boundary and upper boundary value are applied to the operation for analysis.
Output	This text shows the output file name for the analysis. Excel file path is defined with this text.
OK	This button executes analysis based on the input in the dialog and creates worksheet with analysis data.
Cancel	Close the dialog

A.2.3 EDM Operation Dialog

This dialog allows users to define EDM operating conditions and analyse the process. While milling operation dialog is designed to focus on the analysis option, this dialog is designed to define operating condition details. It's because there is not object or functions supported for EDM by Esprit CAM. Hence, operating conditions defined in this dialog is applied to the selected EDM object with pocket geometry for analysis. Figure A.5 shows the dialog box and Table A.3 lists UI components of this box.

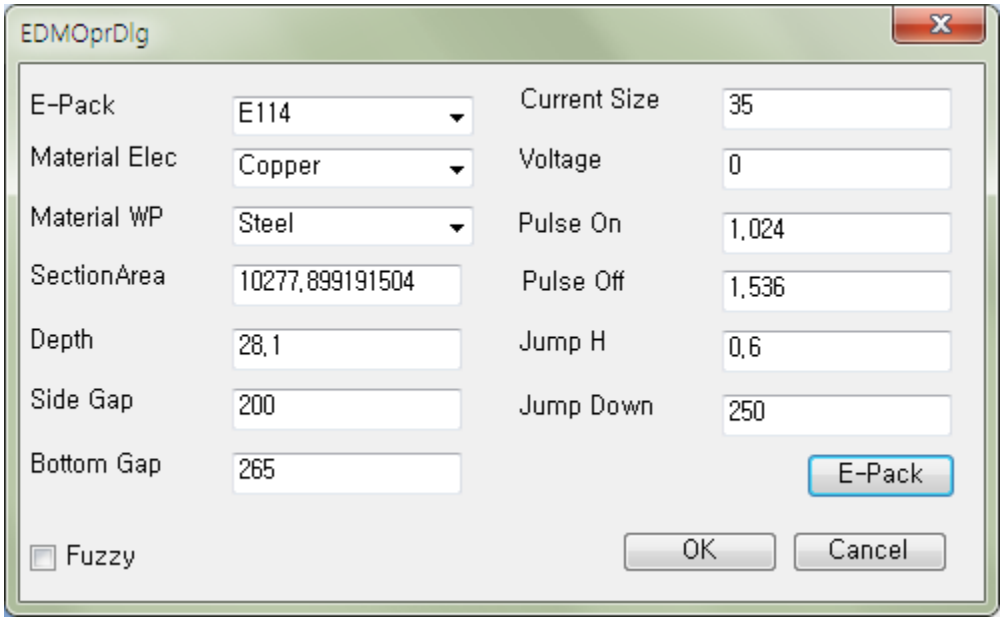


Figure A.5. EDM operation dialog box

Table A.3. EDM operation dialog UI components

GUI Component	Description
E-Pack	This combo box defines corresponding E-Pack database.
Material Elec	Electrode material is selected among copper and graphite.
Material WP	Workpiece material is selected among steel and copper.
Section Area	This box shows section area of the selected electrode. This value is automatically extracted from the pocket information.
Depth	This box shows depth of cavity defined by the pocket information.
Side Gap	This value is the side gap between the selected tool electrode and a workpiece.
Bottom Gap	This value is the bottom gap between the selected tool electrode and a workpiece.
Current Size	This value is the current size applied to the operation.
Voltage	This value is the voltage applied to the operation.
Pulse On	This is the pulse on time of discharge.

Table A.3. EDM operation dialog UI components (Contd.)

GUI Component	Description
Pulse Off	This is the pulse off time of discharge.
Jump H	This is the jump up height for the discharge cycle.
Jump Down	This is the jump down time for the discharge cycle.
Fuzzy	This check box activates fuzzy mode, which allows fixed MRR through the operation. Energy consumption analysis is not implemented yet.
E-Pack	This button loads e-Pack database defined by E-Pack number.
OK	This button executes analysis based on the operating conditions defined in this dialog.
Cancel	Close the dialog