

Environmental Burden Prediction of Manufacturing Process

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Abstract

Emission generated from manufacturing process has become a crucial environmental concern. In addressing this issue, efforts need to be undertaken to mitigate the environmental burden, whose cost will be considered in the near future. This research is developed an evaluation system of environmental burden based on Life Cycle Assessment policy and a preliminary evaluation concept system of environmental burden of machine tool operations is proposed. The total of environmental burden is calculated from the view point of electric consumption quantity, coolant quantity, cutting tool status, lubrication oil quantity, and metal chip quantity of machine tool operations. Global warming is selected as the environmental impact and equivalent CO₂ emission is evaluated. The proposed method is modeled by considering the activities related to the process. The correlation between cutting conditions and the environmental burden which has not been explored so far is analyzed. Some case studies are evaluated in order to show the feasibility and the effectiveness of the proposed method. Moreover, the algorithm of optimization program to determine the appropriate cutting condition to minimize the environmental burden of machine tool operations is implemented and the feasibility of the optimization program is demonstrated.

This thesis is divided into 5 chapters. Chapter 1 is deal with introduction. It includes the background and objective of thesis, brief description about Life Cycle Assessment (LCA) and machine tool operations concept. Chapter 2 explains the evaluation concept for environmental burden of manufacturing process based on LCA (Life Cycle Assessment) concept. This study focuses on global warming. Hence CO₂, CH₄ and N₂O are evaluated and global warming potential of 100 years is considered and equivalent CO₂ emission is evaluated as the environmental burden. Algorithm to calculate environmental burden of manufacturing process is explained in next subchapter. The environmental burden is a total of electric consumption of machine tool components, cutting tool status, coolant quantity, lubricant oil quantity, and metal chip quantity. The algorithm of optimization program to determine the appropriate cutting condition to minimize the environmental burden of machine tool operations which has not been explored so far is analyzed in this chapter.

Chapter 3 describes the experiment of machine tool. The explanation about machine tool used in the experiment, experimental data extraction method, experimental for electric consumption of machine tool operations and example of simulation program are presented in this chapter. Some case studies are evaluated in order to show the feasibility and the effectiveness of the proposed method in Chapter 4. In this chapter, the emission intensities used in the algorithm and other factors required to calculate environmental burden are summarized.

Case study 1 is dealing with comparison of NC programs and coolant usage. The results showed that CO₂ emission mostly emitted from electric consumption compare to other factors and dry machining can be beneficial to minimize CO₂ emission of machining tool operations. The effect of cutting conditions is analyzed in case study 2. The result of analyzed there is a minimum point to realize the minimum environmental burden. CO₂ is the dominant environmental burden in machining operation concerning global warming by comparing CO₂ emission with the equivalent CO₂ emission of CH₄ and N₂O is result for case study 3 while case study 4 analyzed that high-speed milling is effective in reducing CO₂ emission. Chapter 5 consists of conclusions and recommendations of this research.

Abstract (in Japanese)

排出ガスの製造プロセスから重要な環境問題となって生成される。この問題に対処するには、努力を行うことと、そのコストは、近い将来において考慮される環境負荷を軽減する必要があります。本研究では、ライフサイクルアセスメント（LCA）の概念に基づき、工作機械による加工を対象とした環境負荷を事前に評価する手法を提案し、評価概念を開発する。環境負荷は、工作機械の電力量消費や切削油剤の量、潤滑油の量、工具の状態、切屑量から算出している。提案した手法は、加工に関する活動を考慮してモデル化を行っており、これまで実現されなかった環境負荷の観点から切削条件を詳細に比較することが可能である。評価例では、地球温暖化を環境影響項目に設定し、幾つかの加工方法の比較を行い、その有効性を示した。さらに、環境負荷を最小にする切削条件を求めるアルゴリズムを評価概念に実装し、その可能性について示している。

本論文は 5 章から構成されている。第 1 章では、研究背景および本論文の研究目的を述べる。本研究で用いるライフサイクルアセスメント（LCA）、工作機械の操についての説明をおこなう。

第 2 章では、ライフサイクルアセスメント（LCA）の概念に基づき、工作機械による加工を対象とした環境負荷を事前に評価する手法を提案し、評価概念を開発する。本論文では評価対象の環境負荷を、環境影響項目を地球温暖化に設定し、関係する排出物質である CO_2 と CH_4 , N_2O を 100 年間の影響度を示す地球温暖化指標（GWP）を用いて、等価 CO_2 排出量に換算することで求める。また、製造工程における環境負荷を計算するためのアルゴリズムを示す。環境負荷は、工作機械の電力量消費や切削油剤の量、潤滑油の量、工具の状態、切屑量の総和とした。この環境負荷を最小化する適切な切削条件を決定する最適化アルゴリズムを論じる。

第 3 章では工作機械の実験について説明する。この章では、対象とする工作機械、実験データの抽出方法、工作機械の電力消費量実験とシミュレーションプログラムの例についての説明をおこなう。

第 4 章では、提案手法の実現可能性および有効性を示すために、いくつかの加工方法の比較をおこなう。また、アルゴリズムに用いる排出強度および環境負荷を計算するための他の要因について述べる。ケーススタディ 1 では加工における NC プログラムおよび切削油剤の量を変化させて比較をおこなう。その結果、他の要因と比較すると、電力消費量は CO_2 排出量を減少させる主な要因であること、ドライ加工は、 CO_2 排出量を最小化するために有効であることを示す。

ケーススタディ 2 では、環境負荷を最小化するための切削条件を解析する。その結果、環境負荷を最小化する条件が存在することを示す。ケーススタディ 3 では、 CO_2 は CH_4 、 N_2O と比較して加工ツール操作において主要な原因になることを示す。

ケーススタディ 4 では CO_2 を減少させるために高速ミル加工が CO_2 排出量を減少させるのに有効であることを示す。第 5 章は本研究結論および提言で構成される。

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1. Introduction

1.1 Background

Products manufactured generate environmental impact throughout their life cycle; started from raw material extracting and processing, manufacturing, assembling and distribution process, packaging, use and maintenance and at the end of their cycle. The researches about the relationship between machining technologies and environmental impact remains insufficiently discussed and the environmental impact due to manufacturing activities little evaluated.

Manufacturing technologies have been demanded with the goal of delivering a high-productivity and high precision at low cost and short time. However their process generates environmental burden and its reduction is indispensable. Hence, the manufacturing field has been receiving growing attention in recent years. There are many methods have been developed in order to investigate and evaluate the environmental burden of manufacturing process such as Design for Environment (DfE), LCA, Eco-Indicator, and else.

Design for environmental manufacturing involves non-toxic processes and production materials, minimum energy utilization, minimize emissions, and minimize waste, scrap and by-products [1]. While eco-indicator calculates the eco-indicator score of a product in three main stages of its life cycle, for example: production of raw material, processing and manufacturing of these materials, use (transportation, energy and consumables during the life span of a product) and end-of-life (disposal and recycling) [2]. These methods are expected to decrease the effect of manufacturing process to the environment.

The research related to an evaluation system for environmental burden of machine tool operations has previously been done. The reduction in environmental impact of a machining process has been analyzed for turning operation of AISI 1040 steel by considering cutting parameters [3]. But the analysis is only related to the reduction of energy consumption of three different lubrication types (dry, flooded and MQL). Moreover another evaluation system has been evaluated the environmental impact between wet, dry and MQL machining without considering their cutting conditions [4]. Thus, the evaluation system of environmental burden method in turning process using LCA method [5] has been developed. Unfortunately, this method is not applicable for all machining process. Moreover it was found that this evaluation is not practicability since parameters used in this evaluation was obtained from real machining process.

The evaluation system of the LCA of machine tools by considering its secondary effect has been discussed and this concept was applicable to different machine tools [6], but this evaluation method was not explicit. The multi-endpoint environmental effects in manufacturing system planning have been presented [7], but unfortunately the specific method was not addressed to machine tool operations. Hence, it is necessary to develop the evaluation system of environmental burden for machine tool operations towards green manufacturing.

The research to optimize the drilling condition for aluminum material using Taguchi methods in order to reduce the problems such as energy consumption, waste treatment or environmental deterioration experiment focused on the input/output energy relationship is evaluated [8] without considering the cutting conditions and other factors related to the machining process.

Selection of optimal MQL and cutting conditions for enhancing machinability in turning of brass has been analyzed [9] but not consider other factors in machine tool operations. A method described for calculating the optimum cutting conditions in turning for objective criteria such as minimum cost or maximum production rate [10] but not related to the reduction of environmental burden.

As a matter of course, the relation between cutting conditions and environmental burden has not been established yet so far. The cutting speed gets faster and faster in order to pursue high productivity in recent years. The discussions about cutting conditions to realize the minimum environmental burden and about the influence due to the high speed machining are very useful for the future manufacturing. Hence, the aforementioned discussion is carried out based on the evaluation results of the developed environmental burden analyzer in this research.

In this research, a prediction system for the environmental burden of machine tool operations is developed based on the Life Cycle Assessment (LCA) policy. A conceptual architecture and system design for the prediction system is introduced and feasibility and effectiveness of developed system are evaluated in some case studies.

1.2 Objective

The objectives of research are first to develop the evaluation system of environmental burden of manufacturing process; especially machine tool operations, based on LCA policy by considering the emission intensities and other parameters related to the evaluation factor of machine tool operations. Global Warming Potential (GWP) of 100 years impact is taken as a key factor and equivalent CO₂ emission is evaluated.

The total environment burden is evaluated from the electric consumption of machine

tool components, coolant quantity, lubricant oil quantity, cutting tool status, and metal chip quantity. The evaluation is used to simulate and predict the environmental burden of machine tool operations before real machine tool operations occurs.

The second objective is to analyze the relation between cutting conditions and environmental burden of machine tool operations that has not been explored so far. The analysis of cutting conditions to achieve the possible minimum environmental burden is essential for future manufacturing.

1.3 Life Cycle Assessment (LCA)

1.3.1 Definition of LCA

Life cycle assessment (LCA) is a compilation and an evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle [11]. More detailed, LCA is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment, as shown in Figure 1.1; to assess the impact of those energy and materials used and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements [12].

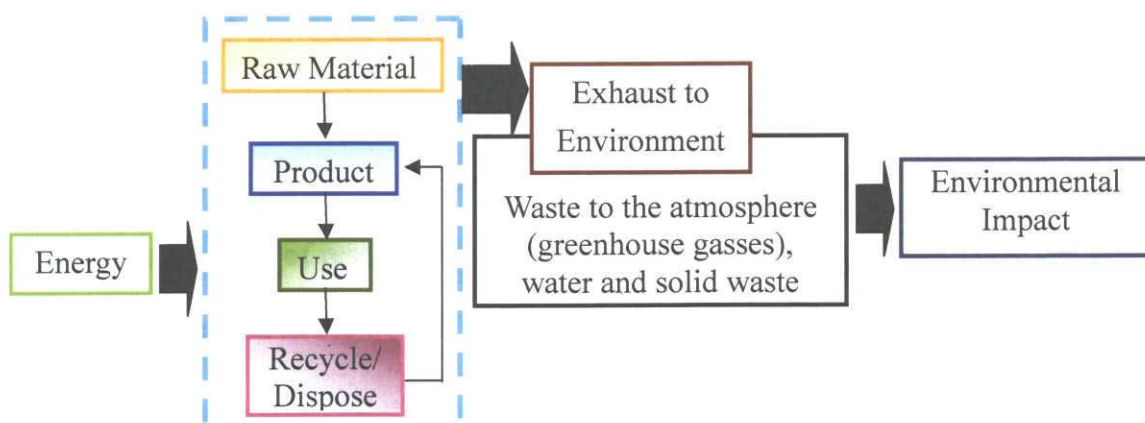


Figure 1.1 Life Cycle Assessment (LCA) Outline

The assessment includes the entire life cycle of the product, process or activity, encompassing, extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal [13]. In addition, in JIS Q 14040 year of 1997 mentioned that LCA is "framework and principles" of international environmental standards (ISO14040) [14]. LCA involves cradle-to-grave analyses of production systems and provides comprehensive evaluations of all upstream and downstream energy inputs and multimedia environmental emissions [15]. In most LCA studies, comparative value is using as a result rather than absolute value.

1.3.2 Goals and Purposes of LCA

The goal of LCA is to define the purpose and method of including life cycle environmental impacts into decision-making process [16]. The primary goal of LCA is to choose the best product, process, or service with the least effect on human health and the environment [17]. Conducting LCA also can help guide the development of new products, processes, or activities toward a net reduction of resource requirements and emissions [18].

1.3.3 Stages of LCA

LCA consists of two main activities; inventory analysis and impact assessment. The inventory analysis describes the emission that might be occurs and the materials and resources used during the life of product. The impact assessment evaluates the impacts of emission and use of resources and raw materials on the environment [19]. The stage of LCA is described in Figure 1.2.

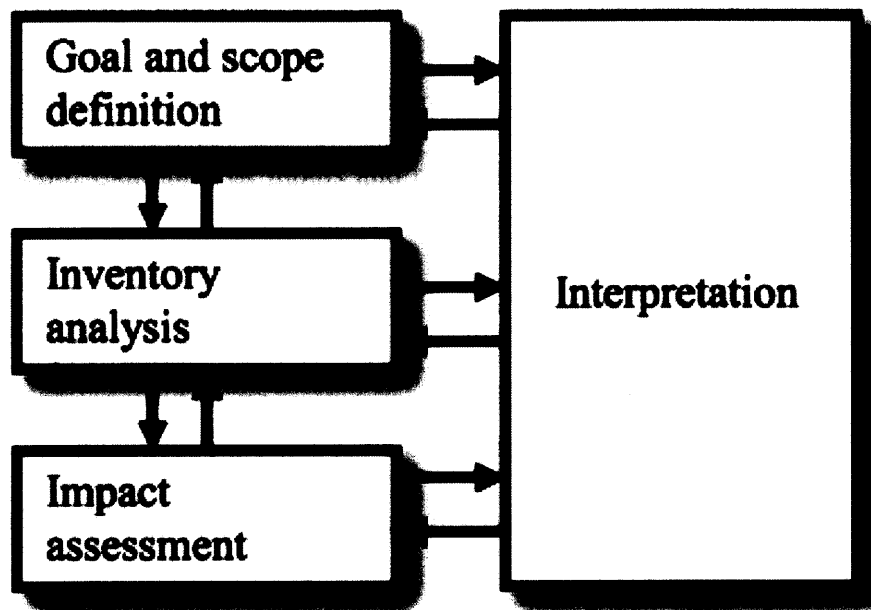


Figure 1.2 Stages of LCA [20]

LCA stage 1: Goal and scope definition

In the goal and scope definition, the LCA is planned. The result of the LCA is very dependent on the decisions taken in this phase. A necessary prerequisite for a good outcome is to initially define the exact objective of the LCA, how the result is going to be used, for which geographical area the result should be apply and so on. Having done this, the more detailed planning can take place.

The detailed planning includes definition of the functions of the product system and the boundaries of the product system. The boundaries should be chosen sufficiently narrow; otherwise the LCA can be very time-consuming, and not necessarily more accurate, because of the uncertainties on data.

If the purpose of the LCA is to compare a number of product systems, the boundaries should be the same for all product systems, and cover all major environmental aspects. Further, the functional unit is extremely important when comparing product systems or alternatives.

LCA stage 2: Inventory analysis

The inventory analysis involves data collection and calculation of inputs and outputs of the product system. Examples of inputs and outputs are use of resources, emissions to air and water.

LCA stage 3: Impact Characterization

The inputs and outputs constitute the basis of the impact characterization. This phase aims at evaluating the significance of the environmental impacts. A typical procedure would be:

- Assigning outputs to impacts categories (e.g. carbon dioxide contributes to global warming)
- Definition of equivalency factors for each impact (for global warming the unit: carbon dioxide equivalents are used and all contributions to global warming are related to this unit)
- Final weighting, expressing how harmful the impacts are in relation to each other, can be applied.

LCA phase 4: Interpretation

The combination of the results from the inventory analysis and the impact characterization facilitate that conclusions and recommendations consistent with goal and scope can be reached.

1.4 Machine Tool Operations

A short introduction of machine tool operations is provided here from the view point of electric consumption, cutting tool, coolant, lubricant oil and metal chip. Machine tools

are devices for cutting materials (mostly metals) into the required shape and size. In metal cutting, the wedge type tool is fed against rotating/translating work piece or vice-a-versa, and chip is produced just ahead the tool by shearing of the metal along the shear plane as depicted in Figure 1.3.

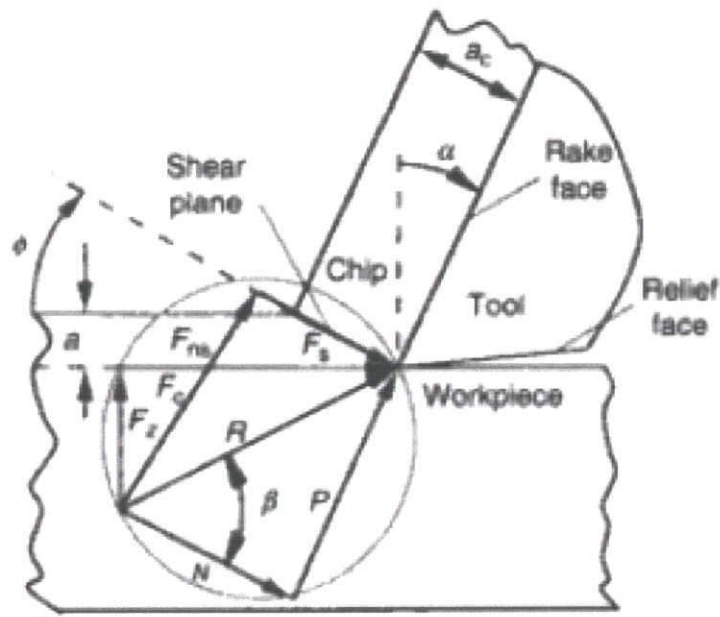


Figure 1.3 Shear Plane Theory of Orthogonal Cutting [21-22]

Machine tool operation is desirable or even necessary in manufacturing process because of these following reasons:

- Performed dimensional accuracy compare to other processes.
- Parts may possess external and internal geometry features that is not able produced by other processes
- Some parts are heat treated for improved hardness and wear resistance in finishing operations
- Accommodate special surface characteristics that can not be produced by other processes
- More economic than other processes

There are a lot of factors involve in machine tool operations, such as electric consumption, cutting parameters, coolant usage, lubricant oil usage, cutting tool, metal chip and others. Each factors are depends on workpiece, shape of product, surface and size of products.

1. Electric consumption of machine tool

The machine tools are composed of various electrical products which consumed during the machining process. Currently, in Japan the total electric power generation, roughly 60 percent came from conventional thermal sources, 29 percent came from nuclear sources, 9 percent from hydroelectric sources, and 2 percent from other renewables [23]. The conventional thermal sources are more likely to emit CO₂ emission compare to other sources.

Machine tool is typically equipped with spindle, servo motor, spindle lubricating oil supply pump, cooling spindle, oil compressor of spindle, coolant pump, chip conveyer, oil mist compressor, oil mist compressor, air blow compressor and tool magazine motor. The electric consumption of machine tool depends on cutting force

2. Coolant

In machining process, friction between tool and workpiece generates heat which affects the dimensional accuracy, surface, metal chip flow and quality of product. Coolant is used in machining process to facilitate lubrication at tool edge and workpiece. Consumption of coolant is one of the critical issues related to the environmental burden of machining process. It is widely known that the effect of coolant on the environment with respect to their degradation and disposal is a major problem. The cost of coolant is approximately 15 percent of the life-cycle operational cost of a machining process. It

includes the costs associated with procurement, filtration, separation, disposal and record keeping for the US Environmental Protection Agency (EPA). Moreover, coolant can have negative effects on the health of the workers.

Recently, there are three types of coolant usage in machining process; wet machining, dry machining and Minimum Quantity Lubrication (MQL) machining. They are divided based on coolant method supply and amount.

1. Wet machining

In wet machining, both the tool and the workpiece are cooled using large quantities of lubricant. Sometimes wet machining called conventional coolant, since it is usually use in conventional machine tool. Wet machining operations is a crucial issues both for economic and environment and also workers healthy.

2. Dry Machining

Machining process carried out in absence of coolant called dry machining. The advantages of dry machining are non-pollution of water, reduced disposal and less danger to workers health. In addition to environmental impacts, an economic factor also plays a major role in choosing dry machining. Researchers are concluded that dry machining is not an option, but a necessity of sustaining competitiveness as the economic issues with coolant is approximately 7 to 17 % of total manufacturing cost which is very high [24-28].

3. Minimum Quantity Lubrication (MQL)

MQL permits dramatic reductions in coolant costs, while protecting workers and the environment. MQL combines the functionality of coolant with an extremely low

consumption of fluids (usually $< 80\text{ml/h}$)[29].

3. Lubricant Oil

Machine lubrication systems are a very important part of machine tool and production workshop maintenance. Lubricant oil in machine tool is used for cooling system for spindle and slide way. The lubricant oil used in spindle must be corresponding to the spindle rotational speed, load, and operating temperature [30]. Lubricant oil systems on modern machine tools are important due to the increasing demands on bearing performance in terms of higher rotational speeds and accuracy. The environmental impact of lubrication oil is minor compare to other factors such as electric consumption or coolant though it is still need to analyze.

4. Cutting Tool

Cutting tool is a tool used to remove metal from workpiece by shear deformation. There are many types of cutting tool in machining process, such as HSS, carbide, and many else. The selection of the right cutting tool is important for achieving maximum productivity during machining. Because it is directly related to the tool wears and tool life; the critical factors in machining process.

Cutting tool performance is affected by cutting conditions, workpiece material and coolant. The environmental burden of cutting tool is related to the used cutting tool. Commonly, used cutting tool is recycled by regrinding and recoating them.

2. Evaluation Concept for Environmental Burden of Manufacturing Process

2.1 System Configuration and Process Flow

The evaluation concept of environmental burden of manufacturing process is shown in Figure 2.1 [31] which consists of the activities inside the manufacturing process such as AGV (Automated Guided Vehicle) loading, machine tool operations, and material handling. In the evaluation concept, pre-manufacturing process simulates and analyzes the manufacturing process before real manufacturing process takes place in order to mitigate the potential environmental burden of manufacturing process.

Resource database stores some parameters for activity analysis such as machine tool specifications, cutting tool parameters, and physical cutting force parameters for the machining process and other parameters related to evaluation factor [32]. Emission intensities database stores emission intensities data required for environmental burden calculation [32]. This research deals with only data related to the production process and disposal process. The data related with other processes are not considered; such as transportation, since the data depend on location and circumstance of user.

The concept analyzes the activities of each process in manufacturing by considering the direct and indirect activities inside the manufacturing process. Direct activities are related to the activities of the manufacturing process such as spindle and slide way movements, lubricant oil, coolant quantity, AGV movement, and material handling operation among others. Indirect activities are not related to the activities of the manufacturing process, such as regrinding of cutting tool, coolant updating, metal chip recycling, lubricant oil updating and else.

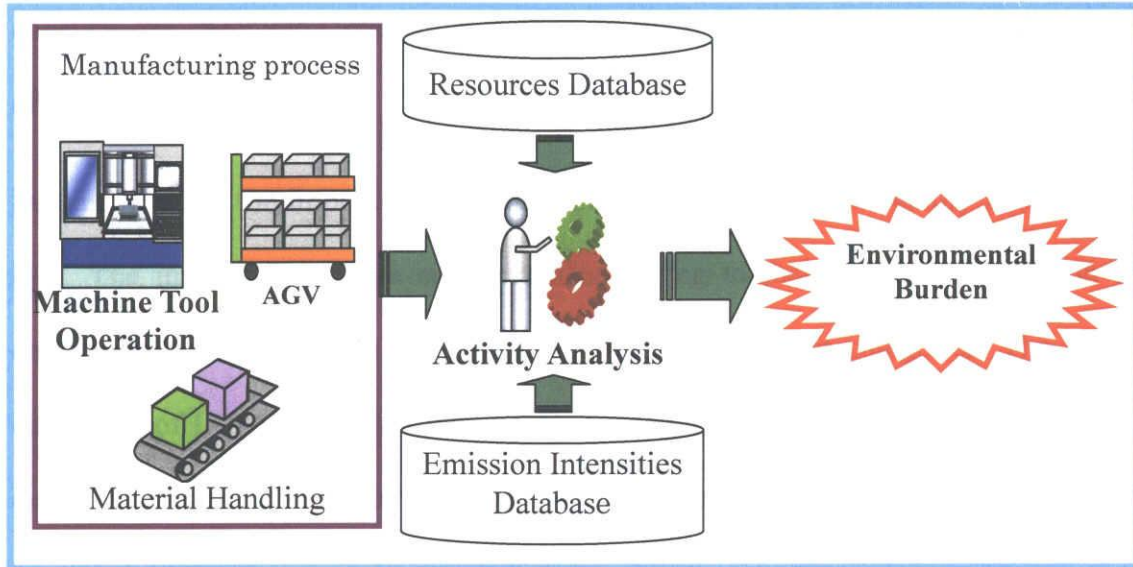


Figure 2.1 The overview of evaluation concept for environmental burden due to manufacturing process

Each component of the manufacturing process provides the information of its activities. For example, AGV in manufacturing process provides the information of transportation time, amount of products transported, electric consumption, and lubricant oil. The information is analyzed by using activity analysis and applying the environmental burden analyzer; therefore the amount of environmental burden of AGV is possible to calculate.

The environmental burden analyzer developed is user friendly. In case machine tool operations, what user need to do are input the NC program, cutting tool type, coolant status (dry, wet or MQL), workpiece size, and other activities related to machining operations into the analyzer and run the analyzer. The analyzer evaluates the activity of machine tool operation above by using resources and emission intensities database and prediction amount of environmental burden of machine tool operation from the viewpoints of electric consumption of machine tool components, coolant quantity, lubricant oil quantity, cutting tool status and metal chip quantity is executed as output. Hence user is able to evaluate cutting conditions prior to real machining operation and

consider the machining operation method in order to reduce environmental burden effectively.

In general LCA, the impact assessment is carried out based on inventory analysis data [33]. The inventory data are categorized according to their potential impact on the environment, human health and resources and called impact categories. The impact categories of LCA are divided into different categories like acidifications, ozone layer depletion, toxicity and global warming [34]. The impact category for this study focuses on global warming.

Table 2.1 Characterization Factors of Global Warming [35]

Green House Gas	CO ₂	CH ₄	N ₂ O
Global Warming Potential	1	25	298

Global Warming Potential (GWP) is used to compare the contribution of different greenhouse gasses to global warming. GWP's are based on time independent index used to compare the specific greenhouses relatives to the CO₂ [36]. GWP of 100 years as depicted in Table 2.1 is considered in this research and equivalent CO₂ emission is evaluated as the environmental burden. Carbon dioxide (CO₂), methane (CH₄) and nitrogen monoxide (N₂O) emissions is evaluated. These emissions are converted to equivalent CO₂ emission by multiplying them with characterization factors of GWP of 100 years impact. The other major greenhouse gases such as fluorocarbons and sulfur hexafluoride (SF₆) are eliminated since these emissions are not generated directly by machine tool operations.

2.2 Algorithm of Environmental Burden Analyzer

Total environmental burden (equivalent CO₂ emission) is the sum of electric consumption of machine tool components, cutting tool status, coolant quantity, lubricant oil quantity, and metal chip quantity. It is calculated by applying the following equation:

$$P_e = E_e + C_e + LO_e + \sum_{i=1}^N T_{e_i} + CH_e \quad (1)$$

where:

- P_e : environmental burden of machining operation [kg-CO₂]
- E_e : environmental burden of machine tool component [kg-CO₂]
- C_e : environmental burden of coolant [kg-CO₂]
- LO_e : environmental burden of lubricant oil [kg-CO₂]
- T_e : environmental burden of cutting tool [kg-CO₂]
- CH_e : environmental burden of metal chip [kg-CO₂]
- N : number of tool in NC- machining process

2.2.1 Environmental Burden of Electric Consumption (E_e)

Electric consumption is determined from running time, but if servo and spindle motor is varied dynamically; depending on a machining process, hence a table weight, a friction coefficient of slide way, a ball screw lead, a transmissibility of a ball screw, a cutting force and a cutting torque are considered. Cutting process simulator [37] is used to calculate the cutting force and the cutting torque. The environmental burden of machine

tool component (E_e) is calculated from the equation as follows:

$$E_e = k \times \left(\frac{SME + SPE + SCE + CME + CPE + TCE1 + TCE2 + ATCE + MGE + VAE}{TCE1 + TCE2 + ATCE + MGE + VAE} \right) \quad (2)$$

where:

- K : CO₂ emission intensity of electricity [kg-CO₂/kWh]
- SME : electric consumption of servo motor [kWh]
- SPE : electric consumption of spindle motor [kWh]
- SCE : electric consumption of cooling system spindle [kWh]
- CME : electric consumption of compressor [kWh]
- CPE : electric consumption of coolant pump [kWh]
- $TCE1$: electric consumption of lift up chip conveyor [kWh]
- $TCE2$: electric consumption of chip conveyor in machine tool [kWh]
- $ATCE$: electric consumption of ATC [kWh]
- COE : electric consumption of oil mist compressor [kWh]
- CHE : electric consumption of air blow compressor [kWh]
- MGE : electric consumption of tool magazine motor [kWh]
- VAE : stand-by of machine tool [kWh]

The environmental burden of electric consumption of machine tool operations depends on cooling system of machining types (wet, dry or MQL). In wet machining process, the

electric consumption of oil mist compressor (*COE*) and air blow compressor (*CHE*) are not considered, while dry machining considers only the electric consumption of air blow compressor (*CHE*) and MQL machining considers the electric consumption of oil mist compressor (*COE*).

The compressor of machine tool is equipped with several sources of equipment. Thus, the calculations of electric consumption for compressors are not simply. Hence, the formula for electric consumption of compressor is constructed as follow:

$$CE_N = CE_r(1 - 0.075(\frac{CP_c - CP_N}{0.1})) \quad (3)$$

where:

CE_N : motor rated output of compressor [kW]

CE_r : motor output needed [kW]

CP_c : discharge pressure of compressor [MPa]

CP_N : discharge pressure necessary to use equipment [MPa]

Equation (4) describes the relation between discharge pressure and motor output needed. The discharge pressure of compressor is 0.7 MPa and if the discharge pressure necessary to use equipment changes to 0.6 MPa, then motor output is impaired about 7.5%.

When using a compressor it is necessary to consider the electric consumption of refrigerated air dryer. The total electric consumption is determined by using the following equation. Here, 30% reduction of motor power consumption when unloading is not considered here.

$$E_C = CE_N + CF + ADFr + ADFa \quad (4)$$

where:

E_C : electric consumption of refrigerated air dryer.[kW]

CE_N : motor rated output of compressor [kW]

CF : motor rated output of fan motor [kW]

$ADFr$: rated output of the refrigerated air dryer [kW]

$ADFa$: fan motor rated output of refrigerated dryer [kW]

As mentioned above, the compressor of machine tool is equipped with several of equipment. The air delivery does not change in any discharge of pressure of compressor (It is assumed to be 1.9 [m³/min]). Air delivery means average air volume discharged under loaded condition, converted into atmospheric pressure. Then, it is necessary to allocate the air delivery of the compressor with the necessary air delivery for the equipment. Formula to calculate the electric consumption of each device describes by following equation:

$$E_N = E_C \times \frac{CAV_N}{CAV_r} \quad (5)$$

where:

E_N : allocation of electric consumption for equipment [kW]

CAV_r : air delivery of compressor [L/min]

CAV_N : air delivery of equipment needed [L/min]

2.2.2 Environmental Burden of Coolant Quantity (C_e)

Coolant is flooding to the cutting edge of cutting tool during the machining process for three main reasons; heat dissipation between cutting tool and workpiece during the cutting process, remove chip produced during cutting process from the cutting area removal and acts as lubrication to ease the friction between cutting tool and workpiece [39]. Coolant usually consists of mixture of soluble oil and water, stored in the coolant tank of the machine tool. Coolant helps to improve tool life and surface finish [40].

Coolant as a cutting fluid consists of two different types; water-soluble cutting fluid and water-insoluble cutting fluid. Water-soluble and water-insoluble cutting oils are commonly used as a cutting fluid or a lubricant to cut metals. A typical example of water-insoluble cutting oils is an oil solution including mineral oil, sulfur, and chlorine. In the meanwhile, a water-soluble cutting oil including mineral oil and the like, to which soap and sulfate are added as an emulsifier or higher alcohol and fatty acid ester are added as a binder, can be used. Water-soluble cutting oil coolant is diluted with water at 10 to 50 times, while non-soluble cutting oil is used without diluted.

The algorithm of environmental burden of coolant for water-soluble cutting fluid type and environmental burden of coolant for water-insoluble cutting fluid type are showed in equation (6) and (7).

The environmental burden of coolant is calculated by considering the circulation of coolant as shown in Figure 2.2. The coolant is stored in the tank and supplied to the cutting area during the machining process through a pump of coolant.

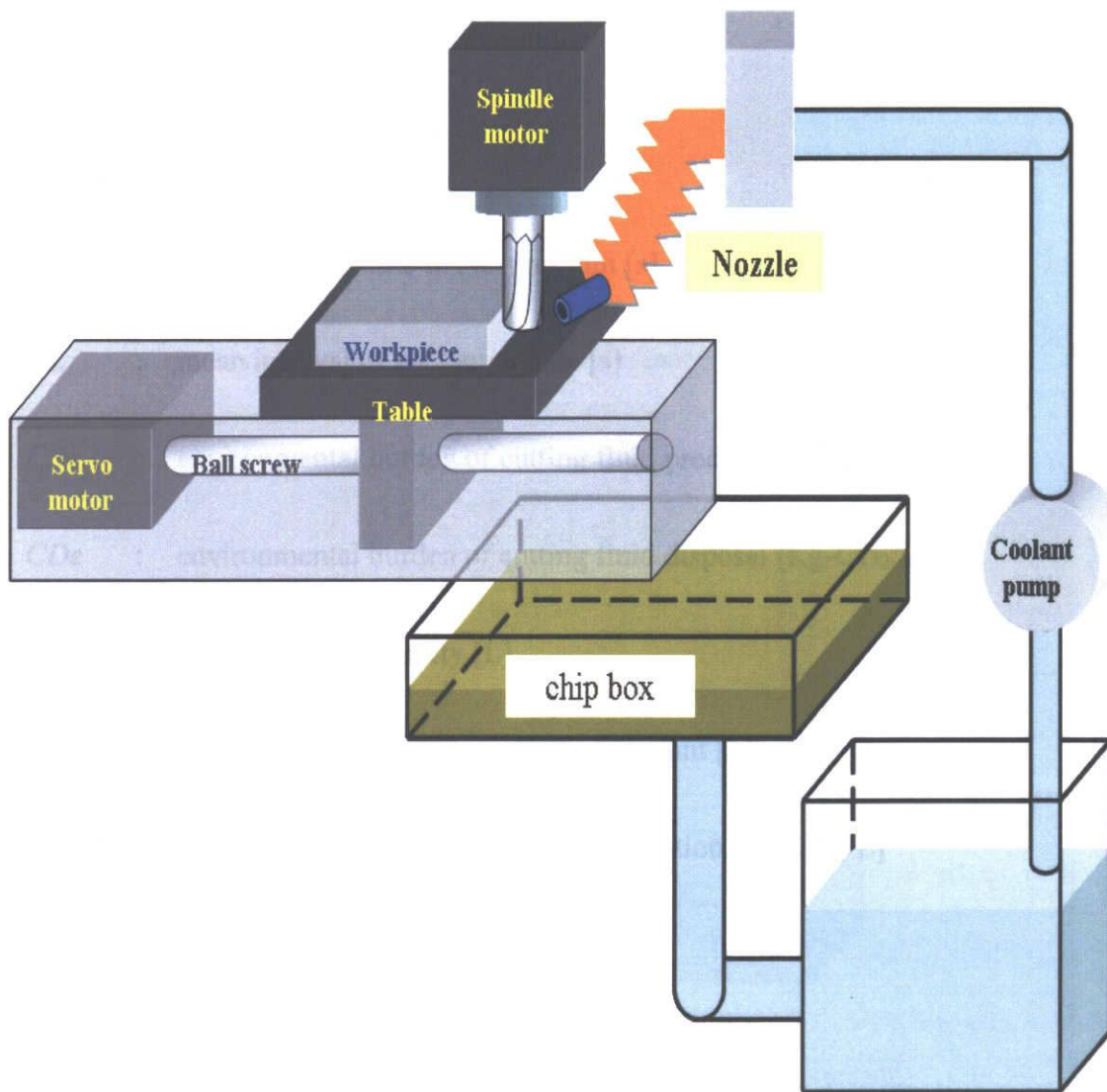


Figure 2.2 Wet machining mechanism systems of machine tool operations

The coolant is restored in the tank and reused again after being separated with metal chip in a catch pan. Cutting oil is reduced gradually due to adhesion to the metal chips; hence the cutting oil is supplied to cover the absence of coolant until coolant is update. Water is also applied due to loss through vaporization at regular periods. The environmental burden of the coolant is formulated by considering the aforementioned process.

$$C_e = \frac{CUT}{CL} \times \left\{ (C_{Pe} + C_{De}) \times (CC + AC) + WAe \times (WAQ + AWAQ) \right\} \quad (6)$$

where:

CUT : coolant usage time in NC program [s]

CL : mean interval of coolant update [s]

C_{Pe} : environmental burden of cutting fluid production [Kg-CO₂/L]

C_{De} : environmental burden of cutting fluid disposal [Kg-CO₂/L]

CC : initial coolant quantity [L]

AC : additional supplement quantity of coolant [L]

WAe : environmental burden of water distribution [Kg-CO₂/L]

WAQ : initial quantity of water [L]

$AWAQ$: additional supplement quantity of water [L]

Wet machining using a large amount of coolant and has become a major environmental impact factors. So, in recent years, MQL type is selected mostly with the compressed air supply to the cutting point in the shape of a tiny amount of coolant mist. The following overview of the MQL system is shown in Figure 2.3.

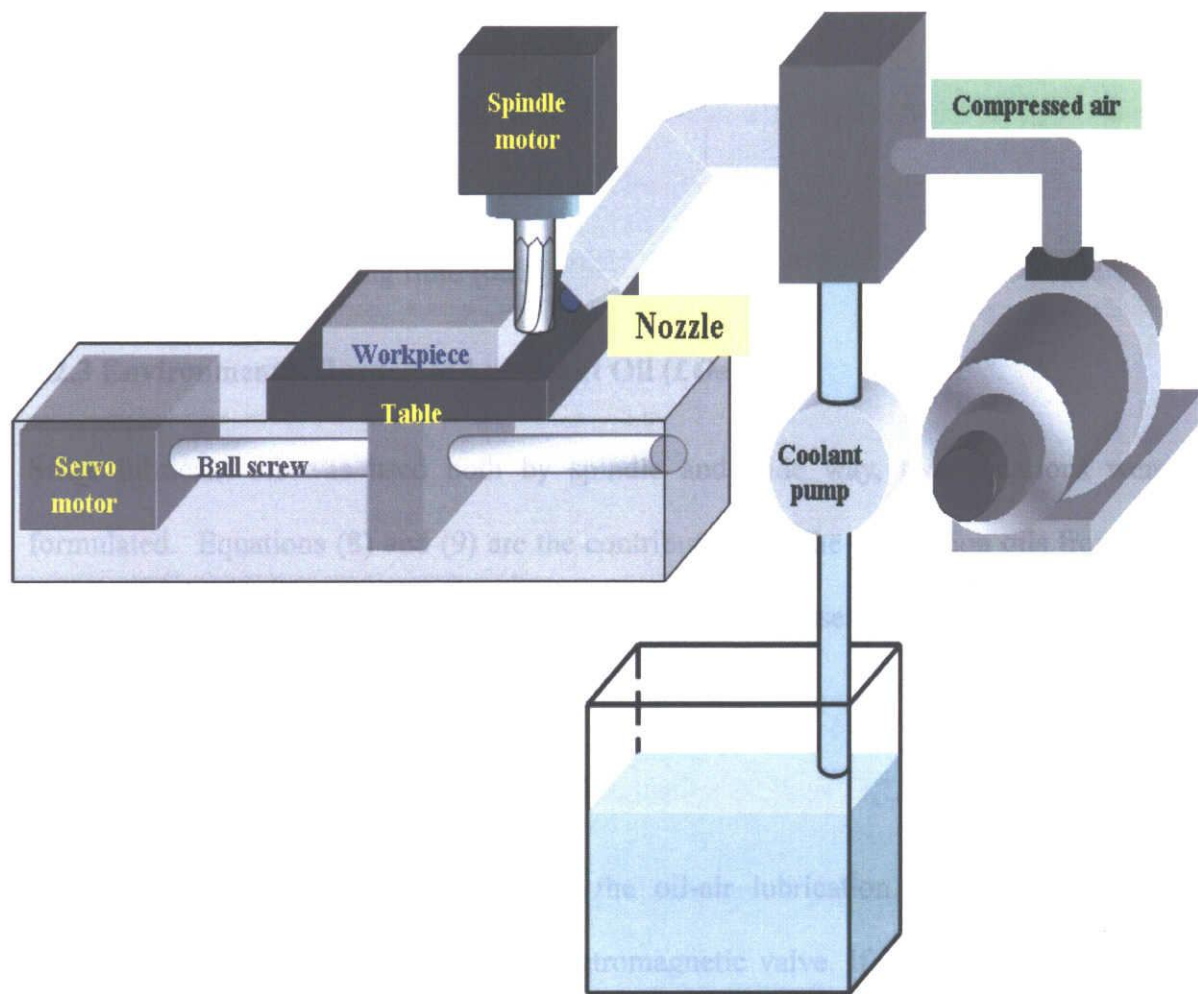


Figure 2.3 MQL System of Machine Tool Operations

Figure 2.3 shows compressed air is added to create the mist which is partially similar to regular fuel. Mineral oil as the main component of the coolant is used, so the oil-based plants will be even less impact on the human impact on the environment. MQL is used to calculate the amount of coolant in the process of taking the time to use one of the coolant and cutting oil consumption per unit of time, to calculate the environmental impact by the Equation (7). Equation (7) shows the environmental burden of coolant (water-insoluble cutting fluid type) where discharge rate is considered as an important factor.

$$C_e = \frac{CUT \times CS}{3600 \times 1000} \times (CP_e + CD_e) \quad (7)$$

where:

CS: discharge rate of cutting fluid [cc/h]

2.2.3 Environmental Burden of Lubricant Oil (LO_e)

Since lubricant oil was used both by spindle and slide way, two equations were formulated. Equations (8) and (9) are the contributions of the lubrication oils from the spindle and the slide way, respectively. Equation (10) expresses the total environmental burden of the lubrication oils.

1. Lubricant Oil of Spindle

Lubrication of spindle is performed by the oil-air lubrication. Oil air lubrication discharge depends on setting timer of electromagnetic valve. If electromagnetic valve opens; according to the setting of timer, compressed air will be activated from the pump making divider of lubricant oil pressure is operated and some fixed quantity of lubricant oil is discharged from compressor air. Therefore, spindle lubrication is lubricated through the nozzle by injected the air lubricant oil into the spindle. The minutes-amount of oil (0.01 cc – 0.06 cc) is injected into an oil pipe by a pump and supplied into a spindle part at decided intervals. The environmental burden of spindle lubricant oil is determined by using the following equation.

$$Se = \frac{SRT}{SI} \times SV \times (SP_e + SDe) \quad (8)$$

2. Lubricant Oil of Slide Way

The lubricant oil of slide way is supplied by a pump at decided intervals. Grease is used as the lubrication oil of slide way. Grease lubrication is not mentioned in equation, but the same equations can be adopted to calculate the environmental burden of lubricant oil of slide way.

$$Le = \frac{LUT}{LI} \times LV \times (LPe + LDe) \quad (9)$$

$$LOe = Se + Le \quad (10)$$

where:

Se : environmental burden of spindle lubrication oil [kg-CO₂]

Le : environmental burden of slide-way lubrication oil [kg-CO₂]

SRT : spindle runtime in NC program [s]

SV : discharge rate of spindle lubricant oil [L]

SI : mean interval between discharges [s]

Spe : environmental burden of the lubrication oil production of spindle [kg-CO₂/L]

SDe : environment burden of the disposal of spindle lubrication oil [kg-CO₂/L]

LUT : slide way runtime NC program [s]

LI : mean interval between supplies [s]

LV : lubricant oil quantity supplied to slide way [L]

L_{pe} : environmental burden of slide way lubricant oil production [kg-CO₂/L]

L_{de} : environmental burden of slide way lubricant oil disposal [kg-CO₂/L]

2.2.4 Environmental Burden of Cutting Tool (T_e)

The environmental burden of cutting tool is examined from the viewpoint of tool life. The cutting tools are recovered by regrinding after reaching their life limits. This relationship is described by the following equation by comparing machining time with tool life:

$$T_e = \frac{MT}{TL \times (RGN + 1)} \times \left\{ (T_{pe} + T_{de}) \times TW + \right. \quad (11)$$

where:

MT : machining time [s]

TL_i : tool life [s]

T_{pe} : environmental burden of cutting tool production [kg-CO₂/L]

T_{de} : environmental burden of cutting tool disposal [kg-CO₂/L]

TW : tool weight [kg]

RGN : total number of regrinding process

RGE : environmental burden of regrinding [kg-CO₂]

2.2.5 Environmental Burden of Metal Chip (CH_e)

Metal chips are collected and recycled in one electric furnace after being separated from the coolant. This process generates environmental burden. However input energy seems

to be different for some metal type. Nevertheless, the electric consumption rate is represented in [kWh/t]; then, the environmental burden is also calculated from the metal chip weight in this study as described as follows:

$$CH_e = (WPV - PV) \times MD \times WDe \quad (12)$$

where:

WPV : workpiece volume [cm^3]

PV : product volume [cm^3]

MD : material density of work piece [kg/cm^3]

WDe : environmental burden of metal chip processing [$\text{kg-CO}_2/\text{kg}$]

2.3 Algorithm to Minimize Environmental Burden of Machine Tool Operations

There are five determining factors that can be considered to minimize the environmental burden of machine tool operations; they are electric consumption, coolant quantity, lubricant oil quantity, cutting tool status and metal chip quantity. The environmental burden of electric consumption, lubricant oil and coolant status depend on machining time, whereas cutting tool depends on tool life and metal chip depends on the number of metal chips formed from cutting process of workpiece. Each factor is variable depending on cutting conditions of machine tool operations. Hence, by varying the amount of each factor, the tendency of spindle speed and CO_2 emission can be described in Figures 2.4 (a) and 2.4(b).

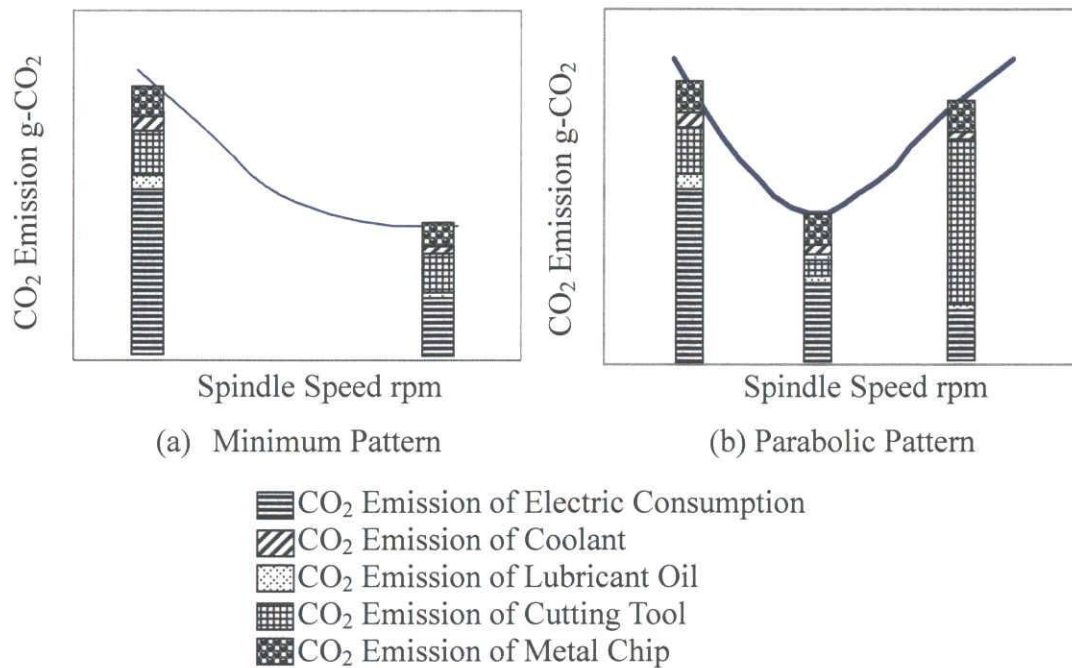


Figure 2.4 Two Patterns of CO₂ Emission of Machine Tool Operations

There are two possible patterns of environmental burden of machine tool operations. Figure 2.4 (a) is a minimum pattern where the total of CO₂ emission is inversely proportional to the spindle speed and reach its optimum point at the highest spindle speed. CO₂ emission is mainly produced by electric consumption. It decreases as the spindle speed increases because machining time is reduced. The same behavior is also observed in coolant and lubricant oil. CO₂ emission generated from the cutting tool and tool life increase with the increase in spindle speed. However, the amount of increase in CO₂ emission of cutting tool is not as high as the decrease in CO₂ emission of electric consumption.

The second is parabolic pattern as depicted in Figure 2.4 (b). It is evident that CO₂ emission is high at the lowest and the highest spindle speeds. Such case occurs because at the lowest spindle speed, machining time is longer and thus electric consumption generates more CO₂ emission. At the highest speed, cutting tool becomes overworked

and its tool life decreases. However there is an optimum point where CO₂ generated is reaching the minimum point.

Figure 2.5 shows the algorithm of the minimization program. Such algorithm is used in order to determine the minimum point of CO₂ emission. Subsequently, the result is used in order to decide the appropriate cutting condition of the machining process. The optimization method is constructed from the two possibly patterns as mentioned above. The mathematical function is determined from the relation of spindle speeds and CO₂ emissions using The Least Square Method. The spindle speeds is iterated until the CO₂ emission generated reaches minimum value.

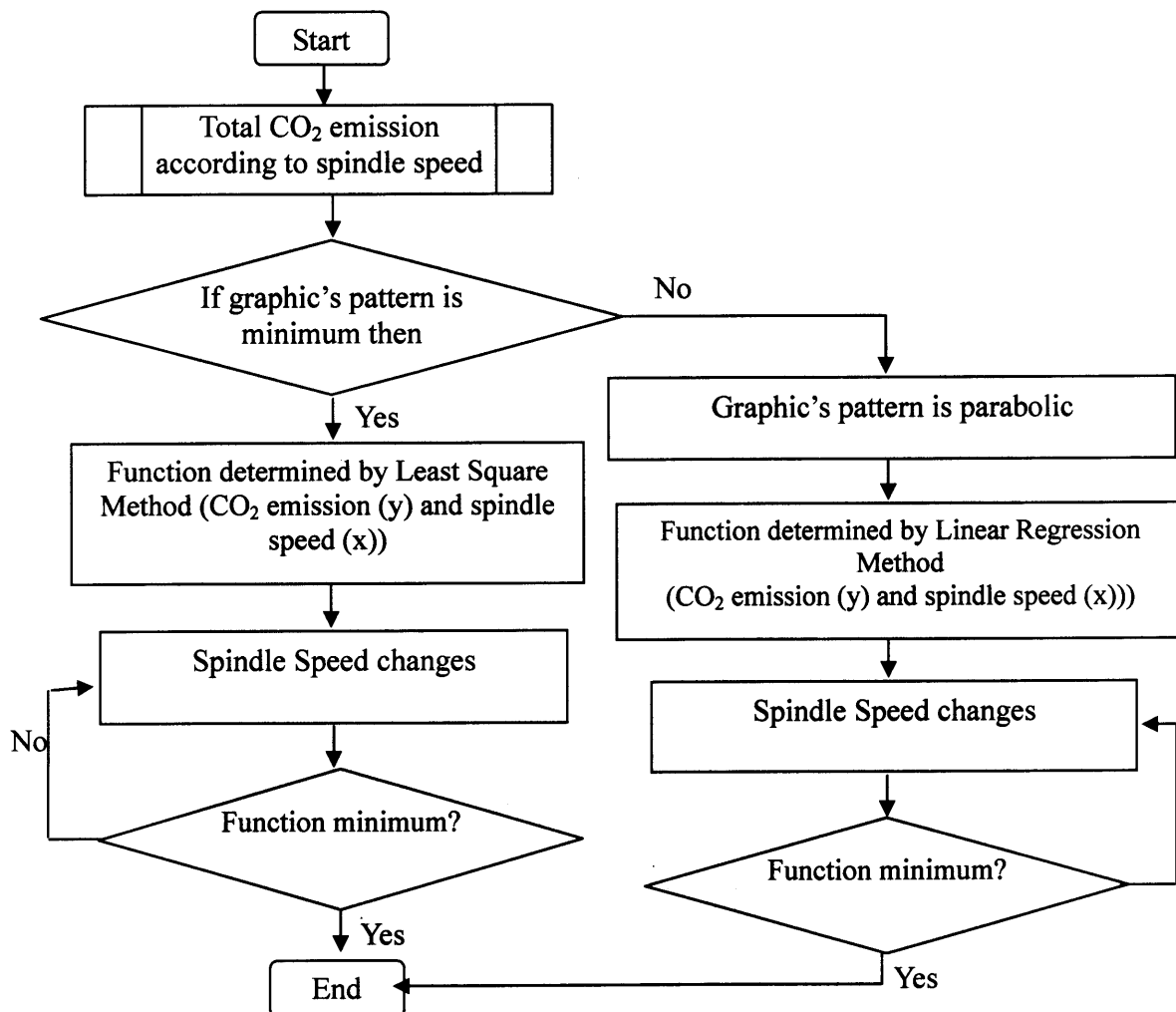


Figure 2.5 The algorithm of minimization program

3. Measurement Experiment

3.1 Machine Tool

Theoretically, the analysis model on the machine tool parameters such as torque, ATC, tool magazine, or others which not listed in the specifications of machine tool such as electric consumption, NC controller, spindle cooling machine, chip conveyer, cooling system of spindle etc are available by doing experiment only.

This research performed by using 3 axis machine tool center MB-46VA (OKUMA) as shown in Figure 3.1. In addition parameters of machine tool are shown in Table 3.1.



Figure 3.1 Machine Tool MB-46VA (OKUMA)

Table 3.1 Machine Tool Parameters

		unit	MB-46VA
Axis Distance	X	Mm	560
	Y	Mm	460
	Z	mm	460
Table	Work plane size	mm	760×460
	Floor~Table top	mm	800
	Maximum capacity loading	kg	500
	Moving part weight	kg	X:905 Y:230 Z:512
Ball screw system	Ball screw lead	m	X,Y:20 Z:16
	Transmissibility of ball screw system		0.95
Sliding surface	Friction coefficient		All axes:0.01(Linear guide)
Spindle	spindle speed	min-1	8,000[15,000 25,000 35,000]
	Spindle motor	kW	11/7.5 (10minute/straight)
			[22/18.5, 15/11, 15]
	Taper		7/24tapertNo.40[HSK-A63, F63]
Feed rate	feed rate	m/min	X·Y: 40 Z: 32
	Cutting feed rate	m/min	X·Y·Z: 32
ATC	Format		BT.40 [HSK-A63, F63]

3.2 Experimental Data Extraction Method

The information obtained from the actual movement of machine tool are electric power, rotating speed, torque and time. The experiment method is shown in Fig 3.2. More detailed, Figure 3.3 depicted the method to obtain the information mentioned above in detail. The factors that not listed in the specifications, is obtained (printed out) directly from the parameter. The amount of electric consumption is possible to determined, however the information from each axis of machine tool is taken by using digital oscilloscope, the amount of voltage is directly input into PC, and by multiply with each axis of the motor, the speed of rotation, torque and time is calculated.

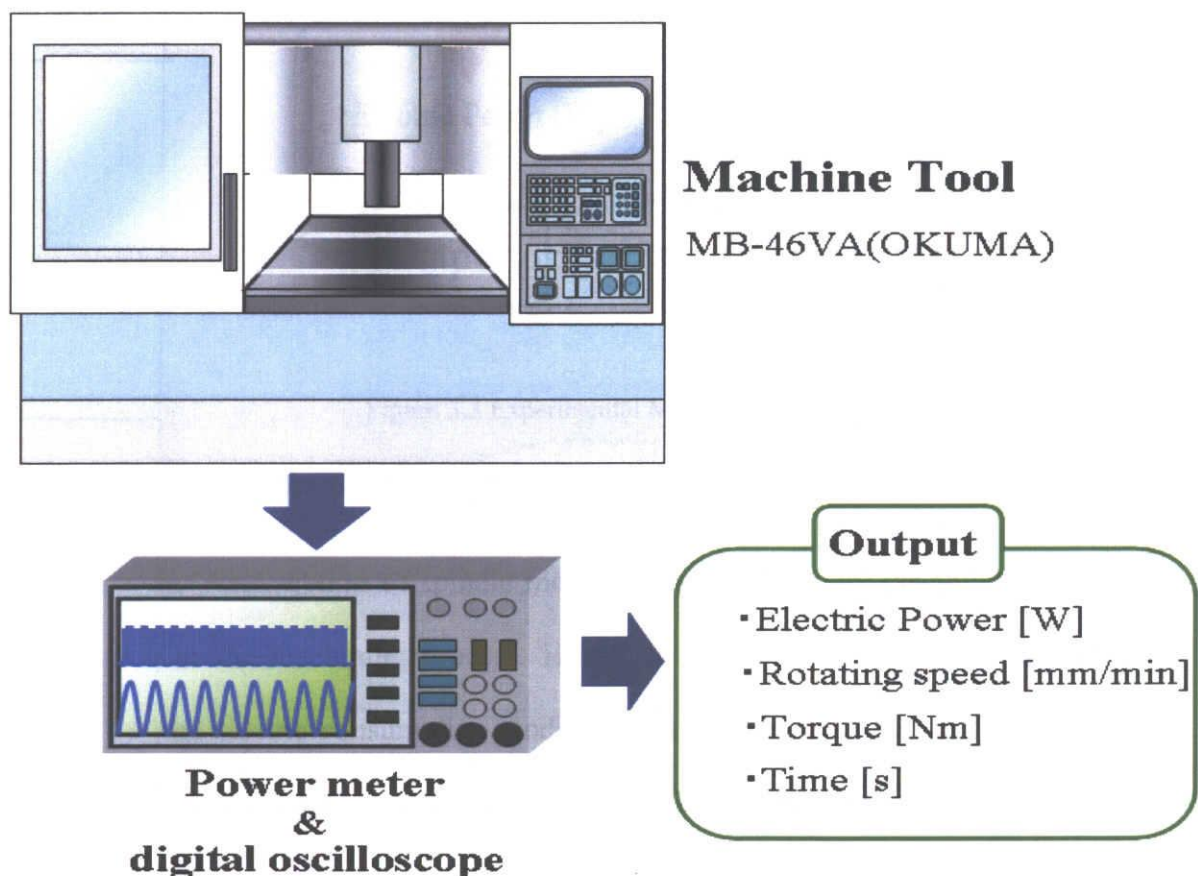


Figure 3.2 Example of Experimental Method

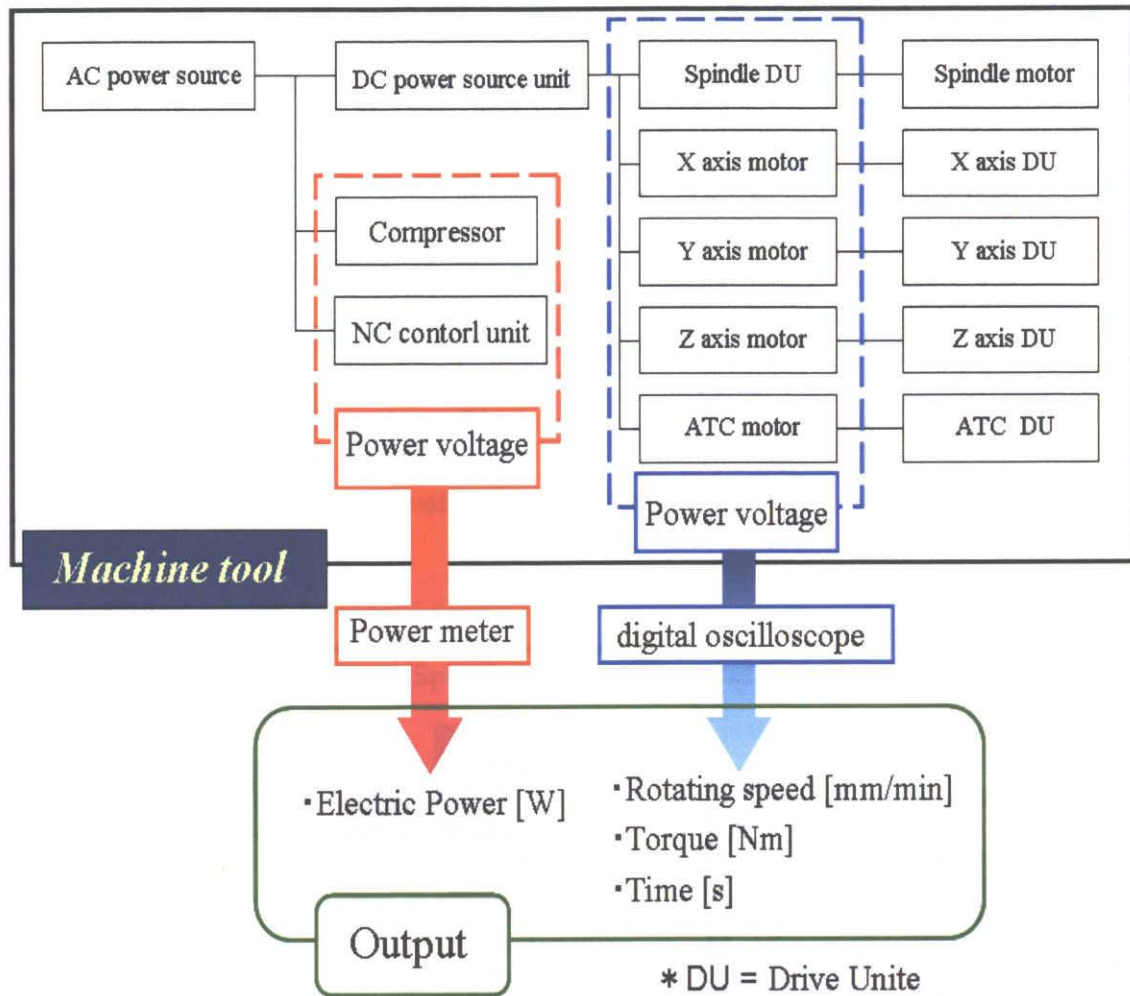


Figure 3.3 Experimental Method in Detail

3.3 Experimental for Electric Consumption

The electric consumption of spindle motor and servomotor are changing dynamically according to the machining process. Hence, it is important to develop the analysis model of the electric consumption model for machine tools as depicted in Figure 3.4. The electric consumption of servo motor and spindle motor is defined by considering transmissibility of ball screw, cutting force, table weight, cutting force and cutting torque whilst the electric consumption of other peripherals (NC controller, coolant pump and ATC) is calculated from running time.

The load torque of spindle motor and servo motor can be determined by the following formula.

$$T_{L1} = T_U + T_M \quad (13)$$

where :

T_{L1} : load torque of servo motor [Nm]

T_U : axis friction torque [Nm]

T_M : operating torque of ball screw [Nm]

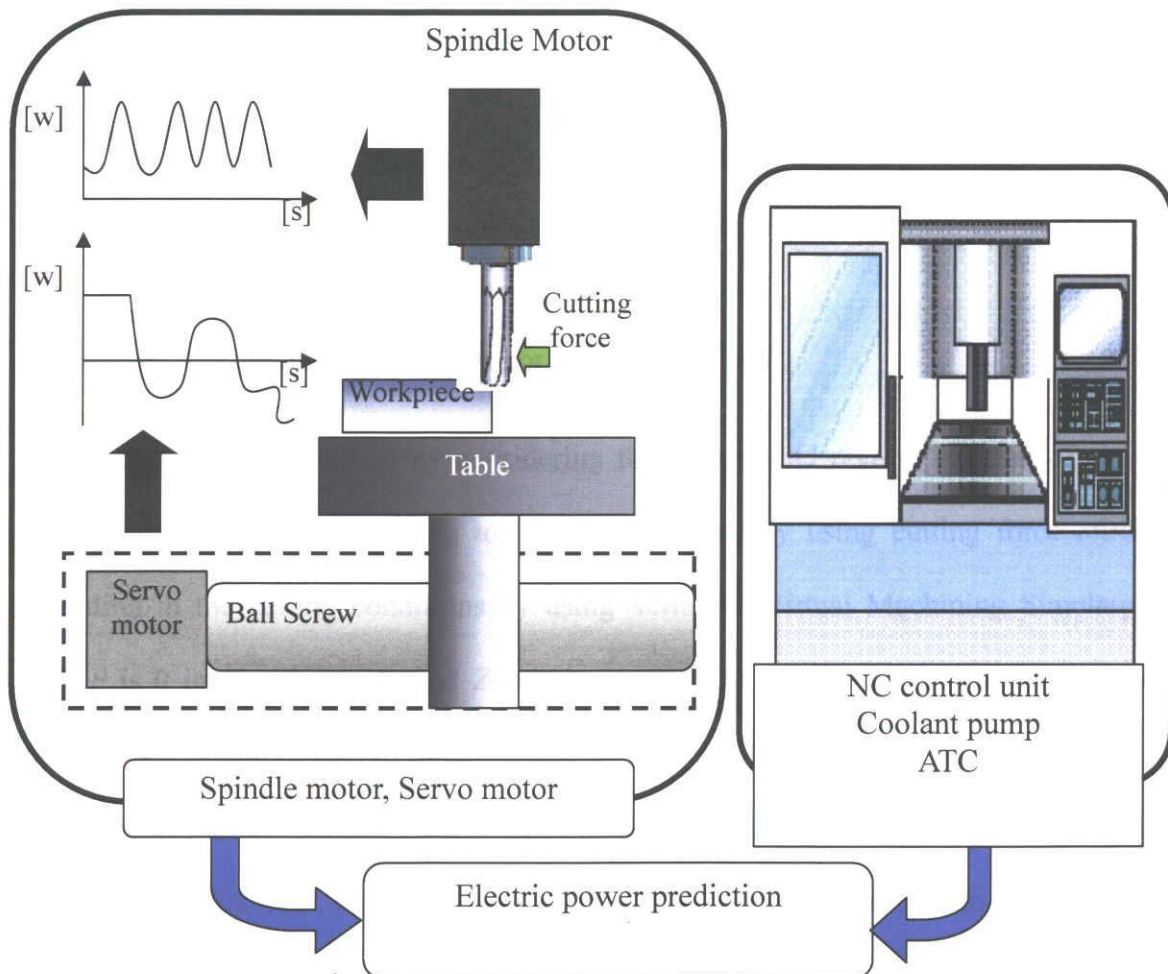


Figure 3.4 Electric consumption models for machine tool operations

The axis friction torque value; T_U , is a torque from the rubber sheet, can not be determined theoretically, but must be determined from the experiment. The operating torque of the ball screw, T_M can be determined by the following equation:

$$T_M = \frac{(\mu \cdot M \mp f) \cdot l \cdot \cos\theta \pm (M - f) \cdot l \cdot \sin\theta}{2\pi \cdot \eta} \quad (14)$$

where :

μ : friction coefficient of slide way

η : transmissibility of ball screw system

l : ball screw lead [m]

M : moving part weight (table and workpiece) [N]

f : cutting force in an axis [N]

θ : gradient angle from horizontal plane [rad]

The equation (14) is defined by considering the normal and reverse rotation of servo motor. Cutting force and cutting torque are predicted by using cutting force model according to the cutting conditions by using VMSIM (Virtual Machining Simulator) [38]. θ is 0 in X and Y axes and Z -axis is $\pi / 2$. The parameters for calculating the electric consumption of servo motor torque are consist of moving part weight (X : 903kg, Y : 230kg, Z : 512kg), friction coefficient of slide way (all axes: 0.01 (linear guide)), ball screw lead (X, Y : 20mm, Z : 16mm) and transmissibility of ball screw system (0.95).

The load torque of spindle motor, T_{L2} is calculated from the cutting force. Equation (15) is using to convert motor torque determined into electric consumption as follows:

$$P = \frac{2\pi}{60} \times n \times T_L \times t \quad (15)$$

where :

P : electric consumption [Wh]

T_L : load torque [Nm]

N : motor rotation speed [rpm]

t : time [hr]

The parameter required for calculating the electric consumption of the servo motor of the machine tool operations shown in Table 3.2 and the electric powers of the peripheral devices of the machine tool are shown in Table 3.3.

Table3.2 Machine Tool Parameters for Servo Motor Torque Calculation

Moving part weight [kg]	X : 903, Y : 230, Z : 512
Friction coefficient of side way	All Axes : 0.01 (Linear guide)
Ball screw lead [mm]	X, Y : 20, Z : 16
Transmissibility of ball screw system	0.95

These values have been measured and obtained from an instruction manual of the machine tool. The electric consumption is, however, listed for an ATC and tool magazine, because they do not depend on their running time. For reference, the machine tool is capable to hold twenty cutting tools.

Table 3.3 Electric powers and consumption

NC controller[kW]	0.16
Cooling system of spindle[kW]	0.45
Spindle cooling machine[kW]	1
Coolant pump[kW]	0.25
Lift up chip conveyor[kW]	0.1
Chip conveyor in machine tool[kW]	0.6
Compressor for oil mist[kW]	0.887
Compressor for chip air blow[kW]	0.887
Stand-by energy[kW]	0.64

3.4 Example of Simulation Program

Simulation program is created and programmed by using C++ programming. The environmental burden analyzer developed is user friendly. What user need to do are input the NC program, cutting tool type, coolant status (dry or wet), workpiece size, and other activities related to machining operations into the analyzer and run the analyzer.

The evaluation method evaluates the activity of machine tool operation above by using resources and emission intensities database and prediction amount of environmental burden of machine tool operation from the viewpoints of electric consumption of machine tool components, coolant quantity, lubricant oil quantity, cutting tool status and metal chip quantity is executed as output. Hence user is able to evaluate cutting conditions prior to real machining operation and consider the machining operation

method in order to reduce environmental burden effectively.

Figure 3.5 shows the example of input program of End Mill program, while Figure 3.5 shown the result of environmental burden of end mill process by using simulation program.

The screenshot shows a software window titled "パラメータ入力" (Parameter Input) with a standard Windows-style title bar and a close button. The window contains several input fields and a dropdown menu, organized into two main columns. The left column contains fields for spindle speed, processing time, machine idle time, tool radius, feed rate, spindle torque, and air flow. The right column contains a section for machine specifications (work machine specifications) with fields for ball screw pitch and table weight, and a section for cutting amounts (cutting volume) with fields for radial and axial cutting amounts. At the bottom, there is a dropdown menu for air source selection and two buttons: "OK" and "キャンセル" (Cancel).

Parameter	Value
主軸回転数[rev/min]	2500
加工時間[s]	50
工作機械の稼働時間[s]	60
工具半径[mm]	6
送り速度[mm/min]	200
軸摩擦トルク[N]	1.5
主軸OA潤滑エア流量[NL/min]	150
150~200NL/min 0.5[MPa]で	
エア源の選択	1 0.7[MPa] 1900[NL/min] 11[kW]
工作機械の仕様	
ボールスクローピッチ[mm]	20
テーブル重量[kg]	905
切り込み量	
半径方向[mm]	3
軸方向[mm]	6

Figure 3.5 Input Parameter Example of Simulation Program

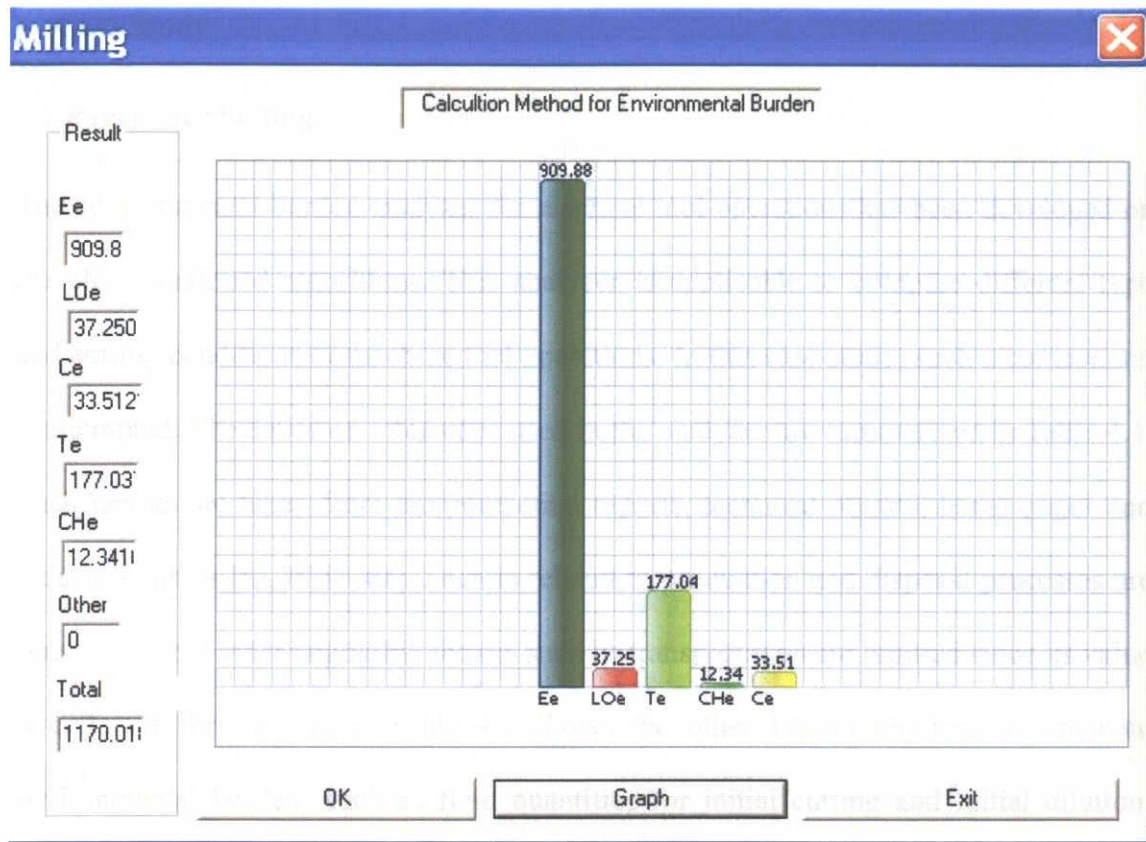


Figure 3.6 Example Simulation Running Program

4. Case Study

4.1 Parameter Setting

The environmental burden analyzer for machine tool operations has been developed on the aforementioned algorithms. This analyzer is applicable to compare different type and cutting conditions of machine tool operations. In this case study, such a comparison is attempted. The emission intensities used in the analyzer are summarized in Table 4.1. Such factors are taken from environmental reports, technical reports, home pages and industrial tables [13,35,41-49]. Factors related to production and disposal processes are considered, but other negligible factors such as transportation are omitted since its value is different for each user. Table 4.2 shows the other factors required to calculate environmental burden, such as fluid quantities for initial cutting and initial dilution. These parameters correspond to the input data filled in by users. The environmental burden analyzer is carried out using this aforementioned data.

Table 4.1 CO₂ emission intensities

Electricity [kg-CO ₂ /kWh]	0.381
Cutting fluid production [kg-CO ₂ /L]	0.9776
Cutting fluid disposal [kg-CO ₂ /L]	0.0029
Dilution liquid (water) [kg-CO ₂ /L]	0.189
Spindle and slide way lubricant oil production [kg-CO ₂ /L]	0.469
Spindle and slide way lubricant oil disposal [kg-CO ₂ /L]	0.0029
Cutting tool production [kg-CO ₂ /kg]	33.7478
Cutting tool disposal [kg-CO ₂ /kg]	0.01346
Regrounding [kg-CO ₂ /number]	0.0184
Metal Chip Processing [kg-CO ₂ /kg]	0.0634

Table 4.2 Other parameters related to the evaluation factor

Fluid quantity for initial cutting [L]	8.75
Additional supplement of cutting fluid [L]	4.3
Fluid quantity and initial dilution [L]	175
Additional supplement of dilution fluid [L]	82.25
Mean interval between replacements of coolant pump [Month]	5
Discharge rate of spindle lubrication oil [mL]	0.03
Mean interval between discharge for spindle lubrication [s]	480
Lubricant oil supplied to slide way [mL]	228
Mean interval between supplies [hour]	2000
Total number of regrinding process	2
Material density of cutting tool [g/cm ³]	11.9
Material density of work piece [g/cm ³]	7.1
Coolant tank capacity of machine tool [L]	175

4.2 Case Study 1 (Comparison of NC programs and coolant usage)

The case study is carried out with the machining center MB-46VA (Okuma Corp). The cutting tool is a carbide square end mill with a 10-mm diameter, two flutes, and a 30° helical angle. The workpiece is medium-carbon steel (S50C). The total depth of the cut is 6 mm with two steps of cutting processes (3mm and 3mm). Figures 4.1(a), 4.1(b) and 4.1(c) show the product shape in 3D view, product shape in 2D view and the tool path pattern of product for two different kinds of simulation programs. In the simulation, we also compared dry and wet machining to confirm the effect of coolant in minimizing the environmental burden.

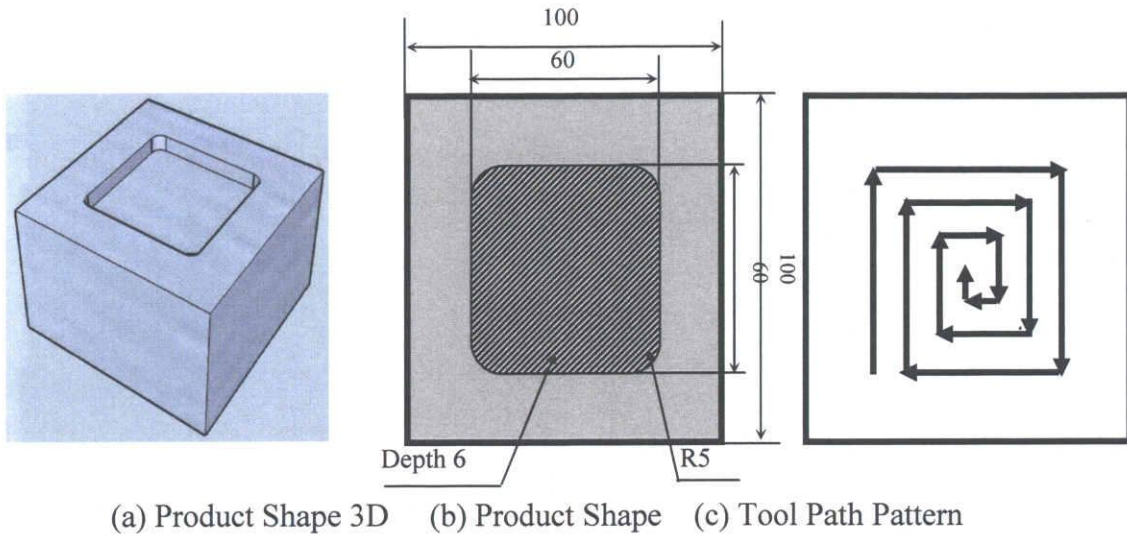


Figure 4.1 Machining Process of Case Study 1

The results of equivalent CO₂ emission for Program 1 and Program 2 are shown in Figures 4.2(a) and 4.2(b), respectively. The spindle speeds and feed rates used in the simulation programs are 2500 rpm and 200 mm/min for Program 1 and 5000 rpm and 400 mm/min for Program 2 respectively. The result shown in Figure 4.2 illustrates that CO₂ emission generated from Program 1 is greater than that of Program 2. Furthermore, machine tool operations without coolant (dry machining) generated low CO₂ emission compared to wet machining in each NC program. Hence, dry machining can be beneficial to minimize CO₂ emission of machining tool operations. High spindle speed and feed rate in program 2 significantly reduce CO₂ emission. In other words, cutting conditions and dry machining adequately reduce CO₂ emission of machine tool operations. In the second case study, the effect of cutting conditions to achieve minimum CO₂ emission is studied in detail.

CO₂ emission mostly emitted from electric consumption compare to other factors. In order to reduce the environmental burden of machine tool operations, the amount of emission generated from this factor must be reduced. Since the electric consumption of machine tool operations is proportional to the machining time, the high-speed milling is

effective to reduce CO₂ emission. Hence, the effect of cutting conditions to reduce CO₂ emission of machine tool operations is discussed in case study 2.

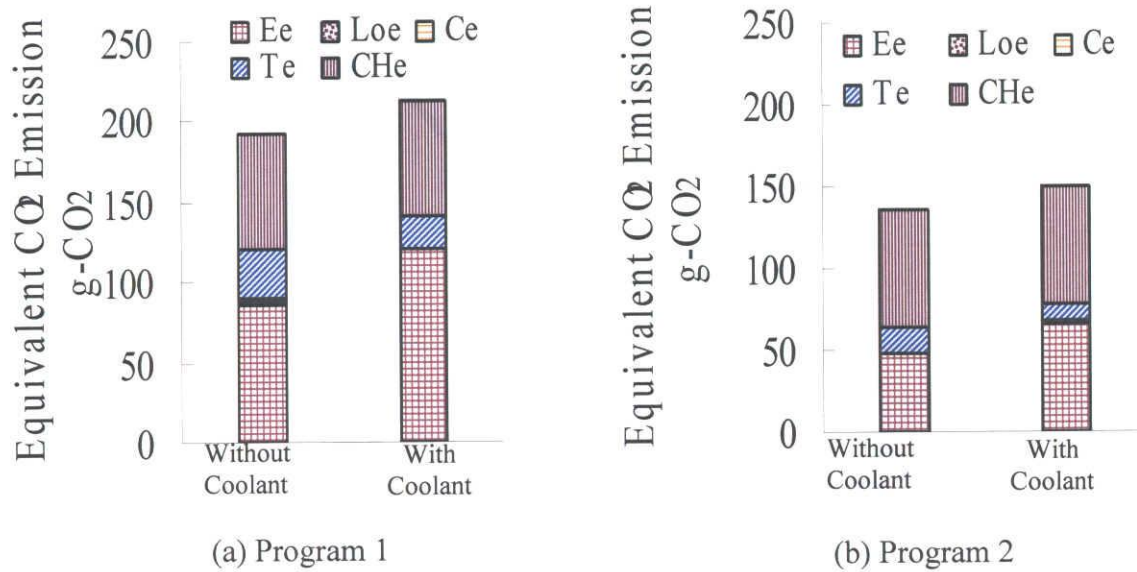


Figure 4.2 Equivalent CO₂ Emission According to Coolant Usage (case study 1)

4.3 Case Study 2 (effect due to the cutting conditions)

There are five determinant factors to determine the environmental burden of machine tool operations. Those factors are electric consumption, cutting tool status, coolant quantity, and lubricant oil quantity and metal chip quantity. Electric consumption, coolant quantity, and lubricant oil quantity depend on machining time, cutting tool depends on tool life and metal chip depends on workpiece and product shape.

Since tool wear increased markedly as cutting speed is increase, the environmental burden of cutting tool is expected to increase due to shortening of tool life. Figure 4.3 shows CO₂ emission of electric consumption decreases as cutting speed increases. While CO₂ emission of cutting tool decreases as cutting speed increases until one point before CO₂ emission of cutting tool increases markedly again. In other words, there is a minimum point of cutting speed to realize a minimum CO₂ emission.

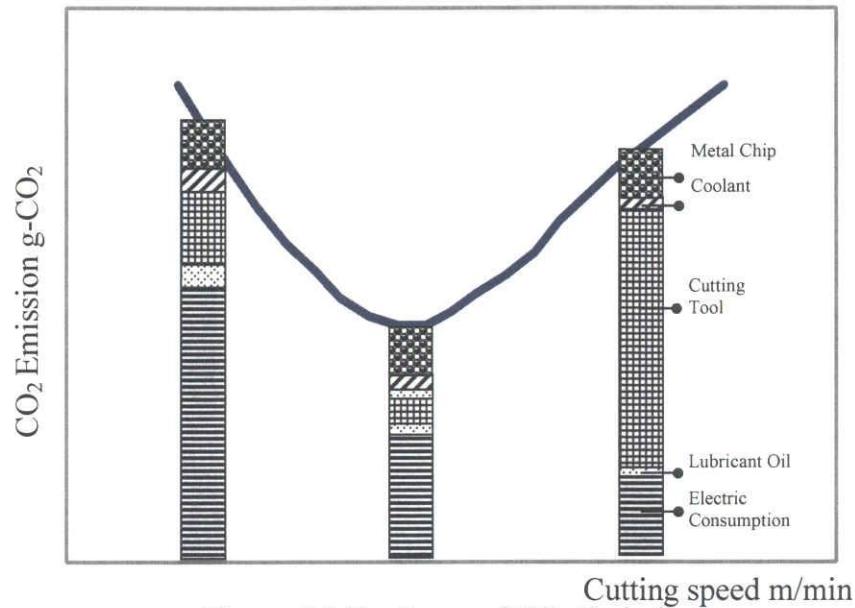


Figure 4.3 Tendency of CO₂ Emissions
According to Spindle speeds

This case study is discussed by using the real tool wear data [36]. In this case study, cutting tool is Ball End Mill, 10mm diameter, and the workpiece is PX5. Cutting speed is varied from 50 to 550m/min, the axial depth is 0.5 mm, the radial depth is 0.8 mm, the feed/tooth is 0.15 mm/tooth and the cutting length is 56.25m.

Figure 4.4 describes the relation of tool wear according to cutting speed. Tool wear is increase markedly after reaches one point because of high cutting speed. The maximum acceptable flank wear is 0.7 mm. Figure 4.5 describes the relation of CO₂ emission according to the cutting speeds respectively. In Figure 4.5, CO₂ emission of the electric consumption decreases but CO₂ emission of cutting tool increases as cutting speed increases. That is to say, there is a minimum point to realize the minimum environmental burden.

This is mainly happened because at the lower cutting speed, machining time is longer and CO₂ emission of electric consumption is major. However, tool wear increases at the

higher cutting speed, it makes CO₂ emission generated of cutting tool is higher than other factors due to the reduction of tool life. Hence, CO₂ minimum realized by decide an appropriate cutting condition using tool wear information provided.

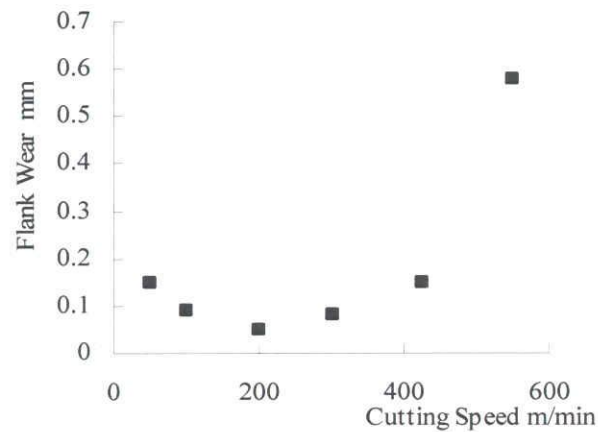


Figure 4.4 Tool Wear According to Cutting Speed

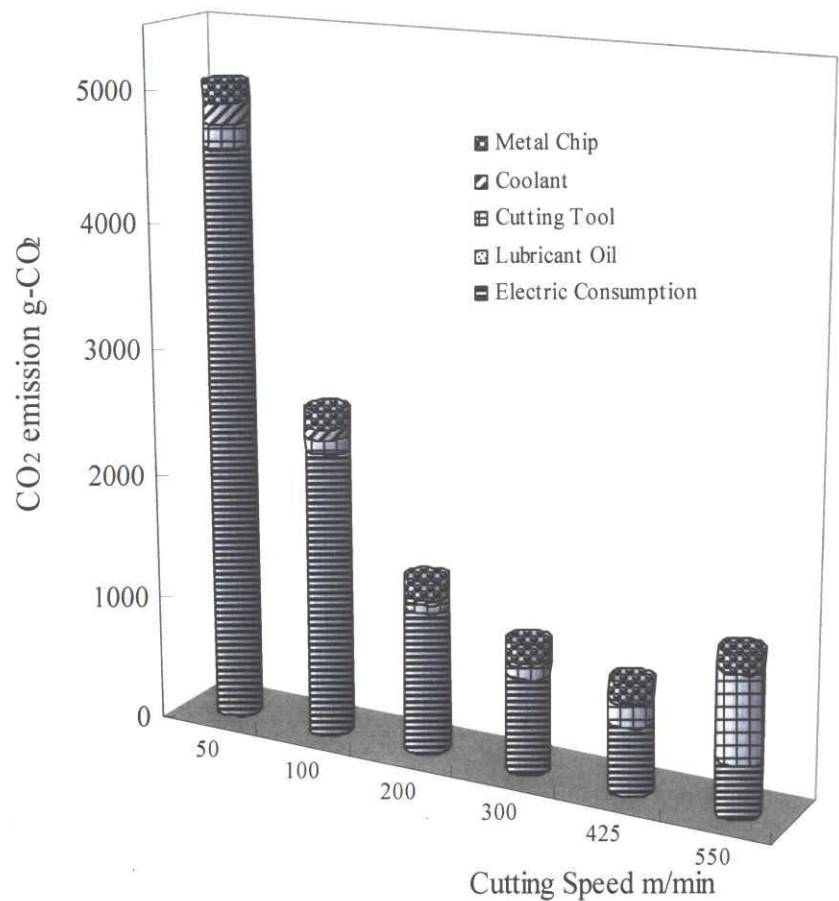


Figure 4.5 CO₂ Emissions According due to Cutting Speeds

In order to decide an appropriate cutting condition to achieve a significant reduction of environmental burden (equivalent CO₂ emission) in machine tool operations, an optimization method is developed. The optimization method is constructed based on the quadratic function as showed in equation (16), determined from the relation of cutting speed and CO₂ emission by using Least Square Method.

$$y = 0.035x^2 - 27x + 55 \cdot 10^2 \quad (16)$$

where:

y = environmental burden equivalent of CO₂ emission g-CO₂

x = cutting speed mm/min

Here, cutting speeds are iterated until the CO₂ emission generated reaches the minimum value. By using this optimization method, it is determined that the minimum CO₂ emission founded at the optimum cutting speed 384 m/min. By applying this cutting condition, CO₂ emission generated is minimum compare to other cutting conditions.

4.4 Case Study 3 (Comparison of cutting method)

For the numerical example, the machine tool is MB-46VA (OKUMA Corp.), the cutting tool is carbide-square end mill with 10 mm diameter, two-flute and a 30° helical angle, and the workpiece is medium carbon steel (S50C). Other parameters input by machine tool users shown in Table 4.3.

Table 4.3 CO₂ Emission intensities for Cutting Fluid Types

Cutting fluid disposal (water-miscible cutting fluid;A1 type) [kg-CO ₂ /L]	3.782
Cutting fluid disposal (water-miscible cutting fluid;A2 type) [kg-CO ₂ /L]	5.143
Cutting fluid disposal (water-miscible cutting fluid; A3 type) [kg-CO ₂ /L]	8.103
Cutting fluid disposal (distilling and condensing process) [kg-CO ₂ /L]	3.425
Cutting fluid disposal (water-insoluble cutting fluid: normal) [kg-CO ₂ /L]	2.555
Cutting fluid disposal (water-insoluble cutting fluid: thermal recycle) [kg-CO ₂ /L]	1.778
Cutting fluid disposal (water-insoluble cutting fluid: material recycle) [kg-CO ₂ /L]	0.261

Figure 4.6 shows the product shape and the tool path pattern used for the evaluation. The spindle speed is 2500 rpm and the feed rate is 200 mm/min. Here, the tool life is assumed to be increased to twofold the original one due to the coolant effect.

Analyzed results are shown in Figure 4.7. The MQL machining is preferable for this machining operation. When we use this evaluation system, we can decide the cutting conditions realizing the minimum environmental burden.

The electric consumption of the peripheral devices of the machine tool, except for the servo motors and the spindle motor and the cutting tool are the main factors in the machining operation from the viewpoint of global warming.

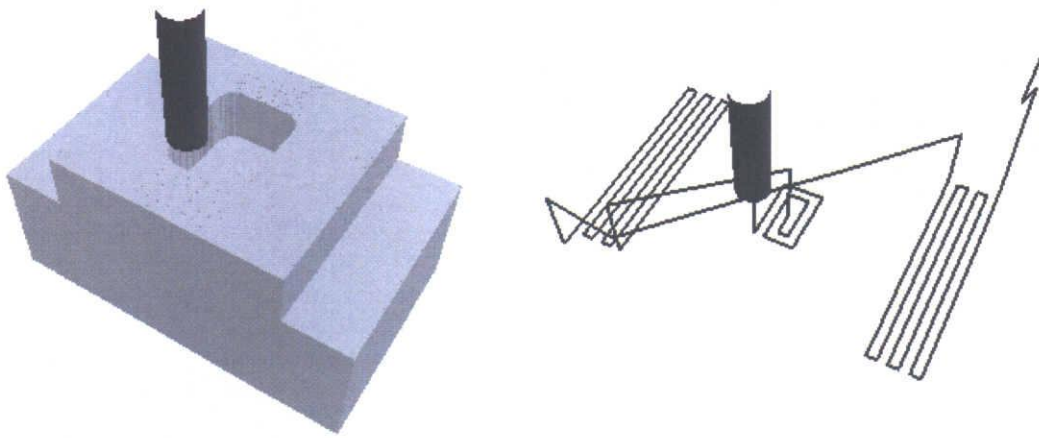


Figure 4.6 Machined shape and tool path pattern

Anyway, the emission intensities of the coolant are very different and not small, however the environmental burden of the coolant is small. It is found that the values of the peripheral devices and the cutting tool must be reduced in order to reduce the equivalent CO₂ emission effectively.

Futhermore, the comparison of the impacts of CO₂, CH₄ and N₂O is carried out. CH₄ and N₂O emissions are occured by the thermal disposal. The impacts of CH₄ and N₂O calculated from Table 2.1 correspond to below 0.001 g-CO₂ by comparing the amount of the emission of each condition. In other words, CO₂ is the dominant environmental burden in the machining operation concerning global warming.

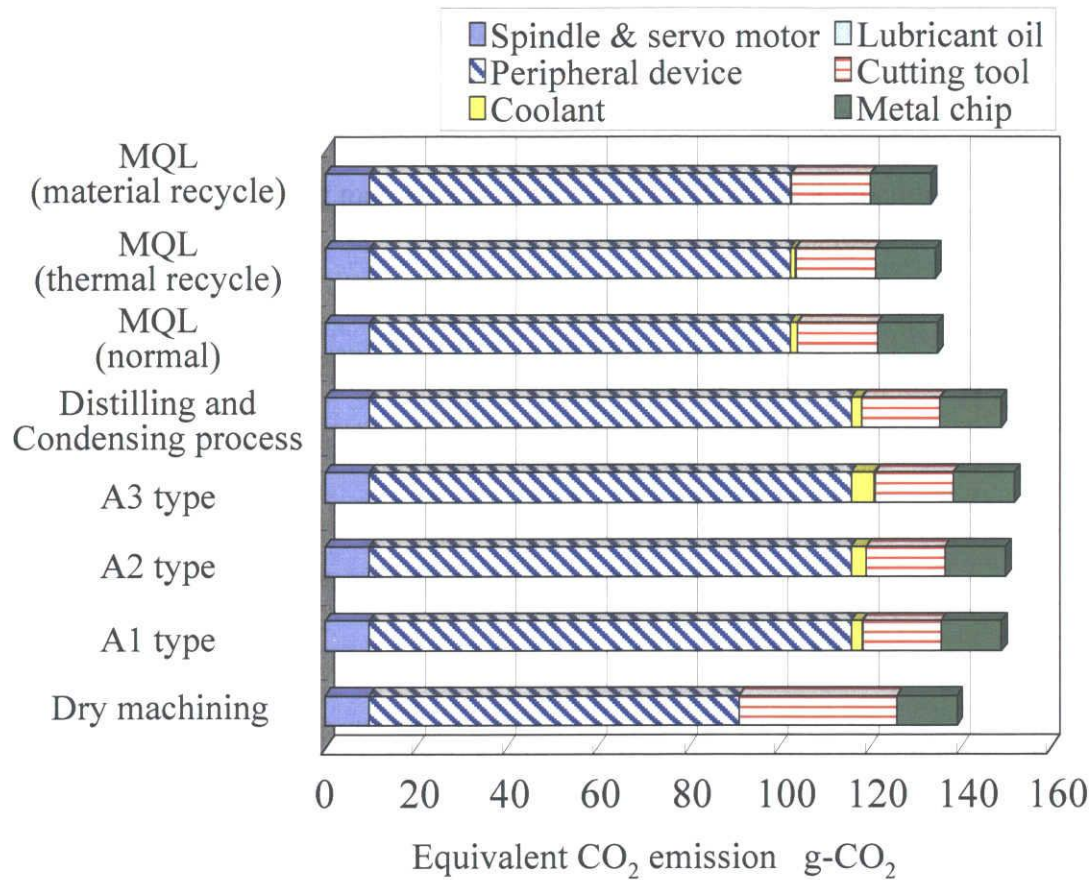


Figure 4.7 Analyzed Environmental Burden Results of Case Study 3

4.5 Case Study 4 (Cutting conditions for minimum environmental burden)

Experiments have been conducted by using machining centre, a cutting tool is carbide square coating with diameter 10mm, flute number is 6, teeth number is 2, helix angle is 30 degree, workpiece is SKD11 (60HRC). In these experiments, cutting speeds were varied from 20 ~ 200m/min and feed/tooth was kept constant. The axial depth is 0.1 mm, the radial depth is 10 mm, the feed rate is 0.1 mm/rev and cutting length is 60m. Airflow is using instead of coolant. These data provided tool wear information and using those tools wears data, environmental burden of high-speed milling is determined. The experimental result, as depicted in Figure 4.8, shows that environmental burden reached a maximum value when at the lowest spindle speed on high-speed milling and

vice versa. This result fits with the minimum pattern of environmental burden mentioned above.

From Figure C-6, by using mathematic (Least Square Method), a function is determined as follows:

$$y = 106346x^{-0.7127} \quad (17)$$

where:

y = Environmental burden equivalent of CO₂ emission

x = Spindle speed

By using this simple equation, it is possible to determine appropriate cutting conditions in order to minimize CO₂ emission.

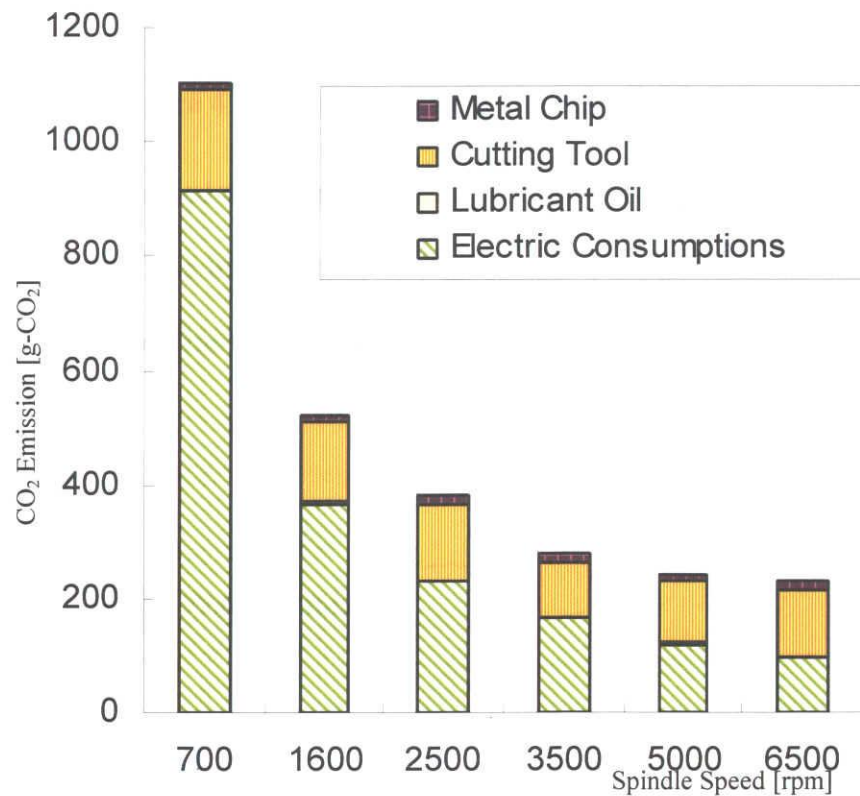


Figure 4.8 CO₂ Emissions due to Spindle Speed

By using a minimization program, we find the optimum point of spindle speed (y axis) which produces the minimum value of CO₂ emission (x axis). From the result, minimum location is located at spindle speed 6365 rpm while CO₂ emission generated is 206.89 g-CO₂. Figure C-7 is shown the minimum point of spindle speed and minimum CO₂ emission more detailed.

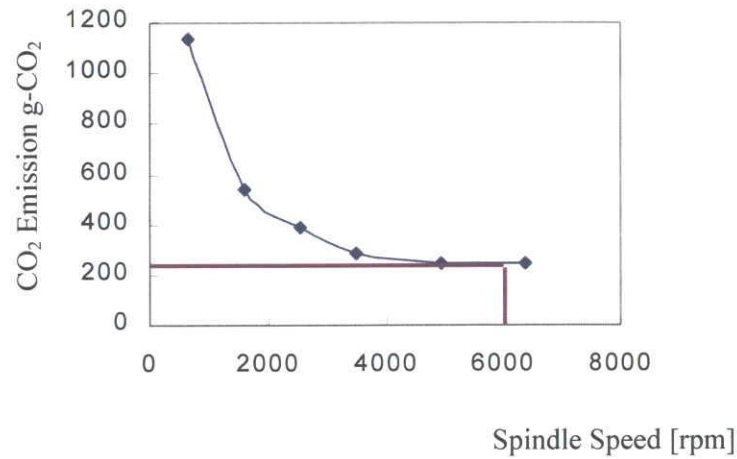


Figure 4.9 Example to Decide the Cutting Condition

Spindle speed is founded 6365 rpm, by using equation (18), CO₂ emission generated is 206.89g-CO₂. From this information, the appropriate cutting condition can be decided.

In this case, we can define cutting condition as follows:

$$V_c = \frac{\pi \cdot d \cdot n}{1000} \quad (18)$$

$$V_c = \frac{3.14 \cdot 10 \cdot 6365}{1000} = 199.681 \text{ m/min}$$

$$V_f = \frac{f_z \cdot z \cdot 1000 \cdot V_c}{\pi \cdot d} \quad (19)$$

$$V_f = \frac{0.1 \cdot 2 \cdot 1000 \cdot 199.681}{3.14 \cdot 10} = 1271.85 \text{ mm/min}$$

Finally, the cutting speed is found at 199.681m/min and feed velocity is 1274.85mm/min. In other words, by using this cutting condition, the CO₂ emissions are high in cases with spindle speeds lower than 3000 rpm and cutting speeds lower than 80 m/min. Therefore, the conventional milling operations emit more CO₂ because they have longer machining time and higher electric consumption.

In contrary, when the spindle speed is higher than 3000 rpm or cutting speed higher than 110 m/min, CO₂ emission decreases and reaches its optimum point at spindle speed 5000-6000 rpm or cutting speed 155-200 m/min. In other words, high-speed milling decreased the CO₂ emission because of the reduction of the electric consumption due to the shortening of machining time. Since the rate of tool wear of high-speed milling compared to conventional milling is decreased, the rate of tool life is also increased and the CO₂ emission generated from cutting tool is decreased. From this analysis, it is found that high-speed milling is effective in reducing CO₂ emission.

5. Conclusions and Recommendations

5.1 Conclusions

The meticulous models for environmental burden (equivalent CO₂ emission) analysis due to machine tool operations have been proposed and the environmental burden analyzer has been developed. The proposed model have been constructed by considering the environmental burden of electric consumptions (with regards to peripheral devices, compressors, spindle motor and servo motor), cutting tool status, coolant quantity, lubrication oil quantity, and metal chip quantity of machine tool operations.

A novel point of the developed analyzer is to evaluate the environmental burden from the difference among cutting conditions from the view point of before a real machining operation. The difference cutting methods (wet and dry operations) are compared, the dry machining was beneficial to minimize environmental burden in the first case study.

The influence of cutting conditions to realize minimum environmental burden of machine tool operations has been discussed in the second case study. We prognosticated that there is a cutting speed to realize minimum environmental burden by evaluating the tendency of five determinant factors (electric consumption, cutting tool status, coolant quantity, lubricant oil quantity and metal chip quantity).

The third case study has showed that CO₂ is the dominant environmental burden in machining operation concerning global warming by comparing CO₂ emission with the equivalent CO₂ emission of CH₄ and N₂O and the forth case analyzed that high-speed milling is effective in reducing CO₂ emission.

The aforementioned prognostication has been proven by the environmental burden analysis according to the various cutting speeds with using real tool wear data. The optimization program to determine the appropriate cutting condition in order to minimize the environmental burden of machine tool operations has been also developed and the feasibility of the optimization program has been demonstrated.

5.2 Recommendations

In the further research, various machining operations will be proposed and analyzed. Moreover, meticulous emission intensities database for evaluates environmental burden should be procured and database for calculate the amount of environmental burden should be constructed according to each process of contributing factors of environmental burden.

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