Title
Software-based tool path evaluation for environmental sustainability

Authors
KONG, DAEYOUNG
Seungchoun Choi
Yusuke Yasui
et al.

Publication Date
2011-10-01

G Model
JMSY-119; No. of Pages 7
ARTICLE IN PRESS
Journal of Manufacturing Systems xxx (2011) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Journal of Manufacturing Systems

journal homepage: www.elsevier.com/locate/jmansys

Technical Paper

Software-based tool path evaluation for environmental sustainability

Daeyoung Kong*, Seungchoun Choi, Yusuke Yasui, Sushrut Pavanaskar, David Dornfeld, Paul Wright

Department of Mechanical Engineering, University of California at Berkeley, Berkeley, CA 94720, United States

A R T I C L E I N F O

Article history:
Received 6 July 2011
Received in revised form 11 August 2011
Accepted 17 August 2011
Available online xxx

Keywords:
CNC machining
Greenhouse gas emissions
Tool-path evaluation
Energy consumption

A B S T R A C T

Currently available life cycle assessment (LCA) tools provide only a rough estimation of the environmental impact of different manufacturing operations (e.g. energy consumption). To address this limitation, a web-based and application programming interface (API) based process analysis software tools were developed to estimate the energy consumption of a computer numerically controlled (CNC) machine tool operation and to evaluate its environmental impact as a first step towards sustainable manufacturing analysis. Acceleration/deceleration of machine tool axes and the direction of axes movement were considered to estimate the total energy demand and processing time of the machine tool operation. Several tool path generation schemes were tested to analyze the energy consumption and resulting green house gas emission of CNC machine tool operation. It showed that tool path generation schemes affect the amount of energy and the processing time required to machine the same part, and location of the machining resulted in different amount and characteristics of green house gas emission.

1. Introduction

CNC machining plays an important role in current mass manufacturing because of its ability to achieve high accuracy and precision as well as its ability to accept computer commands for motion control. The geometric complexity of fabricated products and the large amount of data that a CNC machine tool must process have necessitated the development of computational tools. Simulation software that utilizes computer graphics and numerical analysis has successfully been used to improve the productivity and quality of machining operations. Early work at Berkeley included Cybercut [1] and this was extended to include basic environmental tradeoffs in follow on work [2]. Although manufacturers have become increasingly concerned with sustainability, manufacturing software tools have only just begun to include environmental analyses. Life cycle assessment (LCA) is generally accepted as an effective means to measure environmental impact, but its use in practical development is somewhat limited due to the large amount of time, data, and resources required to conduct it [3]. In case of manufacturing, currently available LCA tools generally focus on unit processes like milling, casting, and forming and provide statistic estimation of the environmental impacts of each process. Although this information is useful for roughly estimating the overall environmental burden of fabricated products, it is not easy to measure the impact of underlying operational variables such as tool path pattern and feed rate. In this paper, we present a software-based approach to supplement general LCA tools by providing greater detail on environmental impacts of manufacturing processes – specifically tool path planning.

2. Background

Machine tools consume significant amounts of electric power during their use phase, which is the biggest source of environmental impact. Enparantza et al. [4] used the life cycle cost (LCC) concept and showed that energy consumption takes about 80% of purchase price of a grinding machine. Diaz et al. [5] analyzed two different machine tools and showed that about 70% of the total emissions come from use phase of those machine tools. Due to the dominance of the use phase in machining, many researchers have focused on reducing the energy consumption of machine tools during the use phase.

To analyze the energy consumption of the use phase, models for individual manufacturing processes have been developed by various researchers, including a model for injection molding [6] and casting [7,8]. Munoz et al. [9] 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. Although their research provides a useful framework for evaluating environmental impact of a machining process, their model covers only cutting processes and excludes other peripheral functions, which include computer, fans and tool change and take larger part in energy consumption than machining as mentioned in [10]. Dietmair et al. [11] introduced a model to predict energy consumption during a machining operation.

* Corresponding author. Tel.: +1 5103636565.
E-mail address: kong0307@berkeley.edu (D. Kong).

0278-6125/$ – see front matter © 2011 The Society of Manufacturing Engineers. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.jmsy.2011.08.005

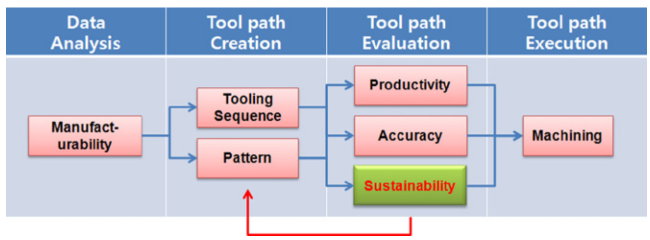

Fig. 1. Process flow for tool path planning incorporating a sustainability concern.

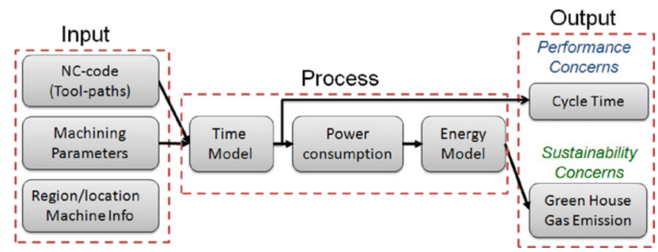

Fig. 2. Architecture of the simulation software.

Besides the studies on the processes, there have been studies focused on the energy demanded to operate a machine tool. Dahmus [10] studied the energy usage of a machine tool by breaking down the energy usage of each component. He adopted the concept of material embedded energy and measured the environmental burden of wasted materials. The work in essence has expanded the scope of the environmental analysis of machining.

Software-based simulation tools have also been suggested as an effective ways of estimating energy consumption and resultant green house gas (GHG) emissions. Narita et al. [12] developed an “environmental burden analyzer” with numerical data and showed how each component of CNC machining comprises environmental burden. Heilala et al. [13] focused on the analysis of the environmental impact, automation level and ergonomics of the manufacturing system. They proposed a hybrid method using discrete event simulation and analytic calculation. Shao et al. [14] summarized the procedure of developing virtual simulation tools of machining.

Tool path data are a main data input for CNC machining and many researchers have evaluated the quality and the efficiency of tool path. Rangarajan et al. [15] argued that there exists an optimal orientation that minimizes cycle time in machining. We expanded this idea to evaluate the environmental impact that a tool path eventually has as a result of its execution in a CNC machine tool. To aid the selection of an effective tool path in terms of the environmental impact in design stage, we implemented software-based simulation tools to evaluate the energy consumption and hence the environmental impact of executing a tool path.

3. Software tool architecture

Fig. 1 shows the process flow for tool-path planning used in our analysis. Two verification steps (data analysis for manufacturability and tool path evaluation for productivity and accuracy) are used in traditional processes. Sustainability as a new measure can be added to the tool path evaluation step.

When target design data arrives, CAM engineers check the design data for manufacturability before developing a machining strategy to see if the design has no problem. 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.

Because of the complexity and the difficulty of tool path evaluation, manufacturing engineers utilize various simulation software tools, whose main objective is to minimize expected problems in machining including undercut, overcut, rapid motion contact, and collisions between 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 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. 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. Fig. 2 shows the structure of the model. The model takes an 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 emission resulting from the material removal behavior of the machine tool to run the NC code, which represent the performance and the sustainability impact of the machine tool operation, respectively. Life cycle of cutting fluid and cutting tool also has the 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 [12,16,17].

4.1. Breakdown of energy consumption

Dahmus [10] investigated the energy demand of individual functional parts of a machine tool and found that the consumed energy that is directly related to machine a part accounts for only small portion of the total consumed energy during machining. That is, while a machine tool is powered on, it wastes large portion of the total energy even during cutting, so called tare energy. Dahmus [10] claimed that almost 76% of the total energy is constantly wasted regardless of the machining status as shown in Fig. 3.

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 [18]. Fig. 3 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 do 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). Since 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), the following analysis is focused on these energy portions.

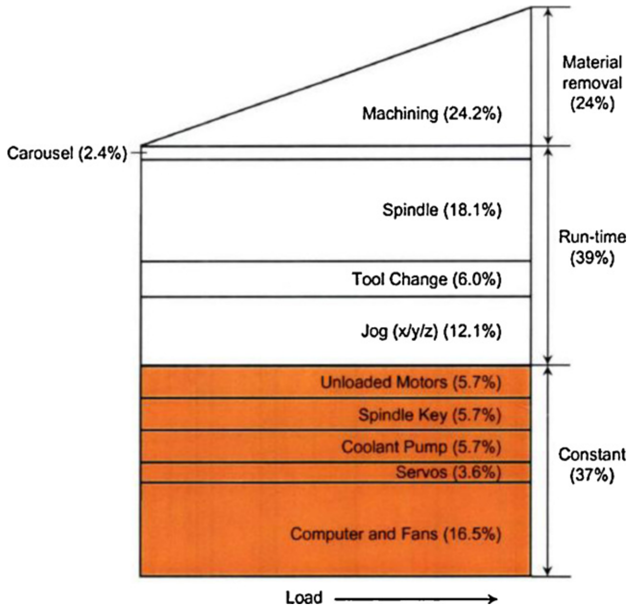

Fig. 3. Machining energy breakdown for a 1998 Bridgeport milling machine [10].

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 or rotational speed for machine axes or 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. We assumed that only the feed rate and the spindle speed influence and are proportional to $E_{run\text{-}time\text{-}steady}$.

$$E_{machine} = E_{const} + E_{run-time} + E_{cut} = E_{const} + E_{run-time-transient} + E_{run-time-steady} + E_{cut} \tag{1}$$

Since a tool path contains motions of machine tool axes that order 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. Utilizing the equations in [19] for the theoretical energy consumption, the following relation was used to estimate E_{cut}:

$$E_{cut} = K_{cut} \cdot w \cdot b \cdot z^p \cdot v_f^{1-p} \cdot n^p \tag{2}$$

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. Experimental data that measures the energy consumption of a machine tool for varied cutting parameters from [19] fitted to Eq. (2) to evaluate the constant p and K_{cut}.

4.2. Acceleration and deceleration

It is well known that tool path segment length and orientation influence machining cycle time. Rangarajan et al. [15] showed that short segment length of a tool path causes longer cycle time and thus the optimal tool path strategy exists that minimizes the cycle time. It also implies that the tool path strategy is related to the energy demanded to produce a product because shorter cycle time can reduce the fraction of the constant tare energy.

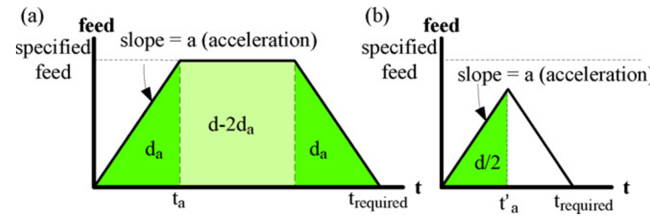

Fig. 4. (a and b) Acceleration and deceleration of machine tool axes to reach a specified feed rate.

Tounsi et al. [20] pointed out that acceleration or deceleration of axes movement needs to be considered to accurately estimate the cycle time and trajectory of the movement of a cutting tool relative to the work-piece. Koelsch [21] reported that there are three types of acceleration profiles: exponential, linear and bell-shaped curves. Among these, bell-shaped curve provides the best performance while exponential curve provides the worst. Besides performance, designers consider controllability of and shock on the machine tools to choose relevant profiles. In this analysis, we used linear curve profile for efficient handling of the relationship between feed rates and position of the axes during machining (Fig. 4). We also assumed that the time required for acceleration or deceleration to a specified feed rate value remains constant, t_a (i.e. the magnitude of acceleration or deceleration is dependent on the feed rate difference before and after the acceleration or deceleration).

Fig. 4 shows two different cases of axis movement that involves acceleration and deceleration. Fig. 4(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 next specified feed rate (zero in this example) after deceleration. Fig. 4(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 is larger than the time to travel the tool path segment.

$$t_{required} = \begin{cases} 2t_a + \dfrac{d-2d_a}{f} & (d \geq 2d_a) \\ \sqrt{\dfrac{2t_a d}{f}} & (d < 2d_a) \end{cases} \tag{3}$$

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 distance of movement corresponds to the area under the curve, 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, making the energy consumption for such a movement decrease. 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.

4.3. Structural configuration of a machine tool and direction of axes movement

Structural configuration of a machine tool also affects the energy consumption of a machine tool because the mass loaded on each axis and the specification of an actuator that drives the axis are different. The energy to drive an axis is simply proportional to the mass loaded on it assuming the same actuator efficiency for all the axes. For conventional vertical machining centers, x-axis is usually placed on y-axis resulting in more mass loaded on the y-axis. This discrepancy in the power requirement for each axis can be resolved

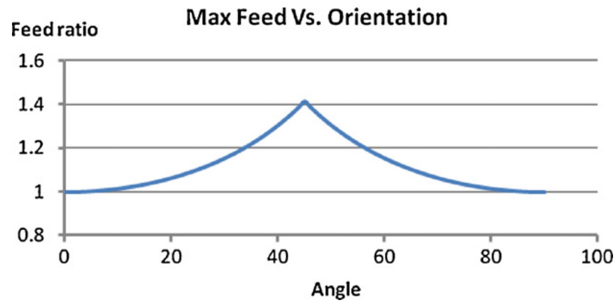

Fig. 5. Maximum feed rate and direction of cutting tool movement.

Table 1
Green house gas emission rates for electricity generation by states.

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

by placing actuators of different power rating or of different number.

Moreover, the movement involving concurrent actuation of two or more axes can attain higher maximum speed as shown in Fig. 5. This calculation is based on the vector addition of two axes. The maximum feed rate in *X* and *Y* direction is assumed to be the same. Hence, maximum feed rate in *X*–*Y* plane is achieved at the 45° orientation.

This implies that there exists an optimal direction where feed rate can be maximized and thereby reduce the cycle time and energy consumption. This result is consistent with the work by Rangarajan et al. [15], who claimed that the direction of cutting tool movement strongly influences the processing time.

4.4. Impact of geographical region on the green house gas emission

Along with the above-mentioned characteristics of machine tools, geographic location choice also affects the GHG emissions associated with electricity consumption [22].

Since each geographical region has a unique dependence on fossil fuels for electricity production, the GHG emitted as a result of electricity use by a machine tool to execute a tool path also varies geographically. To evaluate the influence of the geographically different energy mix (shown in Fig. 6) on the GHG emission during electricity generation, data obtained from U.S. Environmental Protection Agency (EPA) was used [23]. Table 1 shows different GHG emission rates associated with the electricity generation in California (CA) and New York (NY) based on this data. This difference

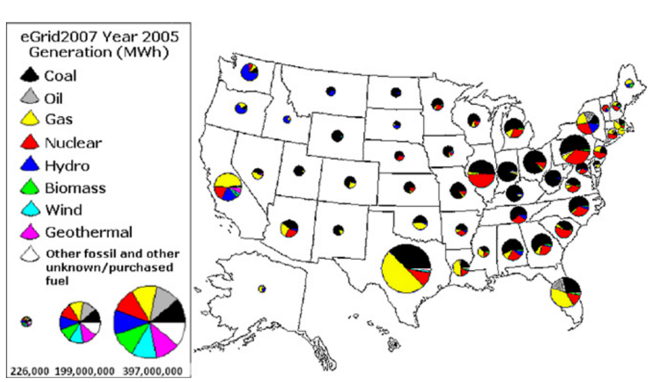

Fig. 6. Energy mix in the USA from U.S. EIA 08 [23].

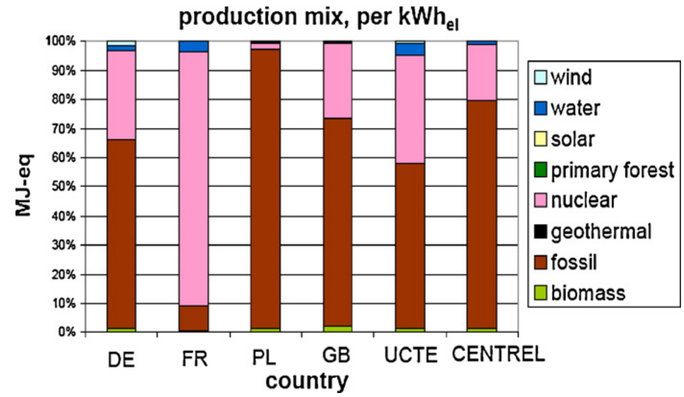

Fig. 7. Energy mix of several countries for electricity generation [24].

results from the fact that while CA depends on gas in large portion, NY depends on coal as displayed in Fig. 6.

This geographical influence on the GHG emission also holds true at a global scale as long as the energy mix varies. Fig. 7 shows the energy mix of several countries for electricity generation. Similar to the previous example comparing CA and NY, the GHG emission in France is very different from other countries in Fig. 7 due to much lower dependency on fossil fuels and higher dependency on nuclear energy.

5. 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.

5.1. Web-based software implementation

In the web-based program, a central database system contains standard information about related machine tool operation and evaluation logics for the 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. Fig. 8 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

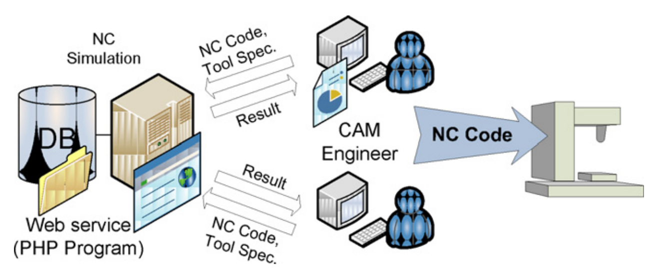

Fig. 8. Web-based simulation environment.

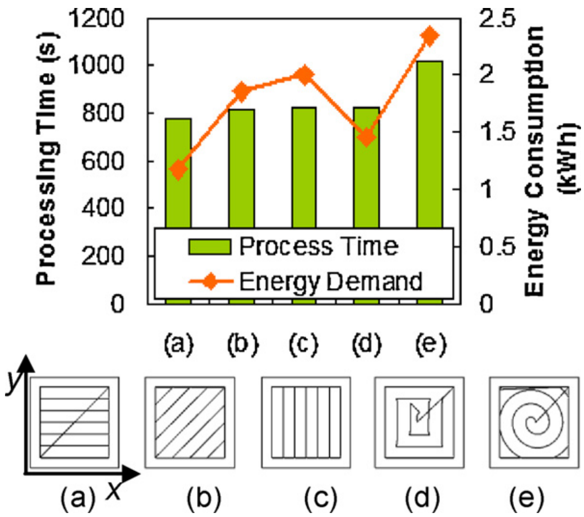

Fig. 9. (a–e) Processing time and energy consumption of various tool-paths.

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.

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.

5.1.1. Test cases

This analysis utilized the structural configuration of a Mori Seiki NV1500DCG. 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 web-based evaluation tool (see Fig. 9). The outermost box shows the edges of the pocket and the curves in the box show the tool paths. A 20 mm diameter flat end mill was used for the rough cutting and a 10 mm 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.

5.1.2. Comparison and analysis

The calculated processing time and energy consumption of the sample tool paths are shown in Fig. 9, which 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).

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 NV1500DCG – 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.

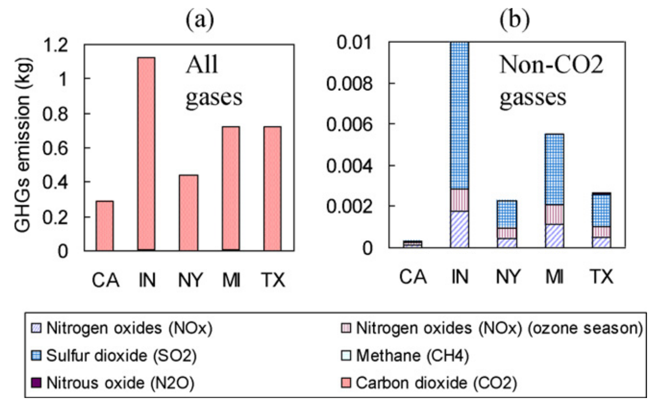

Fig. 10. GHG emissions resulted from executing a sample tool path in five arbitrarily chosen states (figure (a) shows all the GHG emissions and figure (b) shows the GHGs except carbon dioxide).

GHG emissions associated with the operation of the tool path in Fig. 9(a) are compared across five common manufacturing states in U.S. Fig. 10(a) shows the total amount of GHG emission and dominant contribution of carbon dioxide.

Fig. 10(b) shows the other GHGs except carbon dioxide that are not evident in Fig. 10(a). The proportion and total amount of GHG emission reflect the energy mix in Fig. 6. 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.

5.2. API-based software implementation

Most of commercial CAM software providers supply application programming interface (API) in their solutions to allow customization. We used "ESPRIT" CAM software and its API 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 Fig. 11.

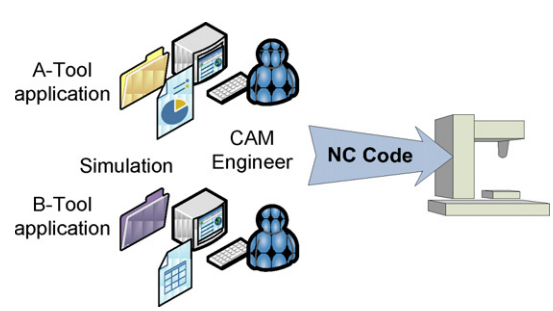

Fig. 11. API-based simulation environment.

Please cite this article in press as: Kong D, et al. Software-based tool path evaluation for environmental sustainability. J Manuf Syst (2011), doi:10.1016/j.jmsy.2011.08.005

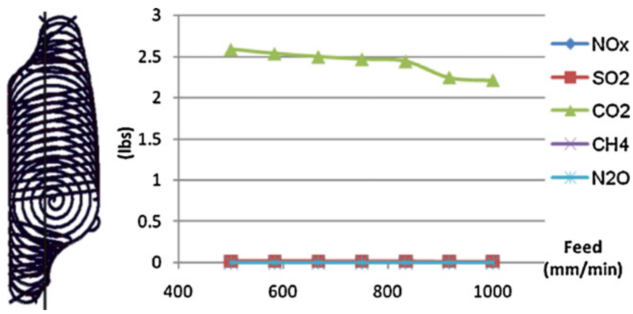

Fig. 12. Green house gas emission as a result of electricity consumption for machining a pocket shown in the left in Indiana.

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.

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.

5.2.1. Test cases

SolidMill Trochoidal pocketing was chosen as the test strategy to machine the curved pocket shape shown in Fig. 12. Seven 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.

5.2.2. Comparison and analysis

GHG emission during the pocket machining in Indiana was evaluated as shown in Fig. 12. It shows that CO_2 is the dominant GHG for all the cases and GHG emission is 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.

Table 2
Comparison of two implementation approaches.

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

6. Conclusion

Two analysis software tools were implemented and tested for milling operations, one of the most important fabrication techniques. Analysis showed that the patterning scheme of tool path influences the amount of energy required to machine the same part. Also, varying the location where the machining is conducted resulted in a different amount and characteristics of green house gas emission. Those findings suggest that better decision can be made by considering both performance and environmental impact.

Comparison of the web-based and the API-based approaches are listed in Table 2. It shows that web-based tools are easier to control and less dependent on the tools in which they are implemented than API-based tools. As a result, the web-based approach gives users more freedom of control than the other. However, the API based approach can provide more benefits from the various functionalities of the tool where it is implemented, and thus more complex functions can be implemented with less effort than the web-based approach. With the same reason, new technologies can be easily updated to the API-based application through the tools where it is implemented.

Approaches presented in this work are applicable to a wide range of areas 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.

Acknowledgements

This work was supported in part by Mori Seiki, the Digital Technology Laboratory (DTL), the Machine Tool Technologies Research Foundation (MTTRF), DP Technology/ESPRIT and other industrial partners of the Laboratory for Manufacturing and Sustainability (LMAS). For more information see lmas.berkeley.edu.

References

[1] Wright P, Dornfeld D. Cybercut: a networked machining service. Transactions of the North American Manufacturing Research Institute, SME 1998;26:281–6.
[2] Dornfeld D, Wright P, Wang F, Sheng P, Stori J, Sundarajaran V, et al. Multi-agent process planning for a networked machining service. Transactions of the North American Manufacturing Research Institute 1999:191–6.
[3] Lindahl M. Engineering designers' experience of design for environment methods and tools-Requirement definitions from an interview study. Journal of Cleaner Production 2006;14(5):487–96.
[4] Enparantza R, Revilla O, Azkarate A, Zendoia J. A life cycle cost calculation and management system for machine tools. In: 13th CIRP international conference on life cycle engineering. 2006:711–6.
[5] Diaz N, Helu M, Jayanathan S, Chen Y, Horvath A, Dornfeld D. Environmental analysis of milling machine tool use in various manufacturing environments. IEEE International Symposium on Sustainable Systems and Technology 2010.
[6] Thiriez A, Gutowski T. An environmental analysis of injection molding. In: Proc. of the 2006 IEEE international symposium on electronics and the environment. 2006:195–200.
[7] Dalquist S, Gutowski T. Life cycle analysis of conventional manufacturing techniques: sand casting. In: Proc. of the ASME international mechanical engineering congress and exposition. 2004.
[8] Neto B, Kroeze C, Hordijk L, Costa C. Modelling the environmental impact of an aluminium pressure die casting plant and options for control. Environmental Modelling & Software 2008;23(2):147–68.
[9] Munoz A, Sheng P. An analytical approach for determining the environmental impact of machining processes. Journal of Materials Processing Technology 1995;53(3–4):736–58.
[10] Dahmus J. Applications of industrial ecology: manufacturing, recycling, and efficiency. PhD Thesis. Cambridge, MA: Dept. Mech. Eng., Massachusetts Institute of Technology; 2007.
[11] Dietmair A, Verl A. Energy consumption modeling and optimization for production machines. IEEE International Conference on Sustainable Energy Technologie 2008:574–9.
[12] Narita H, Kawamura H, Norihisa T, Chen L, Fujimoto H, Hasebe T. Development of prediction system of environmental burden for machine tool operation (1st report). Transactions of the Japan Society of Mechanical Engineers, C 2006;71(704):1392–9.

Please cite this article in press as: Kong D, et al. Software-based tool path evaluation for environmental sustainability. J Manuf Syst (2011), doi:10.1016/j.jmsy.2011.08.005

[13] Heilala J, Vatanen S, Tonteri H, Montonen J, Lind S, Johansson B, et al. Simulation-based sustainable manufacturing system design. In: Proc. of the 2008 winter simulation conference. 2008:1922–30.
[14] Shao G, Kibira D, Lyons K. A virtual machining model for sustainability analysis. In: Proc. of the ASME 2010 international design engineering technical conferences & computers and information in engineering conference. 2010.
[15] Rangarajan A, Dornfeld D. Efficient tool paths and part orientation for face milling. CIRP Annals: Manufacturing Technology. 2004;53(1): 73–6.
[16] Narita H, Desmira N, Fujimoto H. Environmental burden analysis for machining operation using LCA method. In: Proc. 41st CIRP conf. on manufacturing systems. 2008:65–8.
[17] Narita H, Fujimoto H. Environmental burden analysis due to high speed milling. In: Transactions of 19th international conference on production research. 2008.
[18] Devoidere T, Dewulf W, Deprez W, Willems B, Duflou J. Improvement potential for energy consumption in discrete part production machines. In: Proc. of 14th CIRP international conference on life cycle engineering. 2007:311–6.
[19] Tönissen S. Power demand of precision machine tools. MS Thesis. Berkeley, CA: Dept. Mech. Eng., University of California, Berkeley; 2009.
[20] Tounsi N, Baileyb T, Elbestawia M. Identification of acceleration deceleration profile of feed drive systems in CNC machines. International Journal of Machine Tools and Manufacture 2003;43(5):441–51.
[21] Koelsch J. Unleash your CNC's power. Manufacturing Engineering 2006;137(3).
[22] Reich-Weiser C, Dornfeld D. A discussion of greenhouse gas emission tradeoffs and water scarcity within the supply chain. Journal of Manufacturing Systems 2009;28(1):23–7.
[23] U.S. Environmental Protection Agency. eGRID2007 version 1.1 year 2005 summary tables. http://www.epa.gov/egrid; 2008.
[24] Frischknecht R, Tuchschmid M. Energy supply: electricity mix updates. 2nd international ecoinvent meeting; 2008.